Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia

Prepared by

The Karst Task Force

for the

Resources Inventory Committee

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Preface

The *Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia* describes provincial standards for conducting karst inventories at various survey intensity levels, and outlines procedures for deriving karst vulnerability ratings.

This document builds upon the recommendations and proposals for conducting karst inventories and vulnerability assessments described in *A Preliminary Discussion of Karst Inventory Systems and Principles (KISP) for British Columbia* (Research Program Working Paper 51/2000). The KISP document was widely reviewed by national and international karst experts, industry, and by staff from the Ministry of Forests and the Ministry of Environment, Lands and Parks.

It is intended that these standards and procedures be implemented on an interim basis for a two-year period. This interim period will be utilized to collect practical field data and user feedback.

The karst inventory and vulnerability assessment processes contained in this document are designed to be used in conjunction with the karst management guidelines outlined in the *Karst Management Handbook for British Columbia* (BC Ministry of Forests, 2001). Experience from both inventory and operational applications will be used to field test the RIC standards to ensure they apply effectively and efficiently to all parts of British Columbia. At the end of the two-year interim period, a revised set of standards will be published.

Abstract

This report describes standards and procedures for conducting karst inventories and vulnerability assessments in British Columbia. The information provided here was developed for the Resources Inventory Committee (RIC), a multi-disciplinary committee responsible for establishing provincial inventory standards.

Karst inventories can be conducted at three levels: 1) the reconnaissance-level inventory; 2) the planning-level inventory and vulnerability potential mapping; and 3) the karst field assessment (KFA) and vulnerability assessment. The three levels of inventory provide a filtered approach to evaluating karst terrain, with each level having increased requirements for data collection and evaluation.

Reconnaissance-level karst inventory work for the entire province of British Columbia was completed in 1999. The result of this work is a set of 87 map sheets (1:250 000 scale) outlining those areas in the province that have the potential for karst development. These maps can be used to assist with strategic planning and for directing more detailed karst inventories.

Planning-level karst inventories are used to obtain a general sense of the karst attributes for an area of interest at the landscape level. This information can be used to assist resource planning, provide data for karst vulnerability potential mapping, and identify areas that require a more detailed KFA.

The planning-level procedure describes an office phase and a field phase. During the office phase, all available information for the area of interest is collected and compiled. There are six major field tasks associated with a planning-level inventory: 1) bedrock geological mapping; 2) karst mapping and evaluation for vulnerability potential; 3) identification of significant surface karst and hydrological features; 4) evaluation of the karst catchment; 5) identification of karst flora and fauna, and associated habitats; and 6) identification of geomorphic hazards.

Rating of karst polygons for vulnerability potential is a qualitative evaluation based on: 1) the primary attributes of epikarst development, surface karst feature density and subsurface karst potential; 2) the secondary attributes of surficial material type and thickness, bedrock type and proportion and karst micro-topography; and 3) the tertiary attributes of slope class, drainage class, geomorphic processes and other surface expressions. The presence of unique or unusual flora/fauna or associated habitats can be used to increase the vulnerability potential rating of some polygons.

Karst field assessments (KFAs) are carried out at the site level to obtain detailed information on karst resources within and adjacent to an area of proposed development, and to assess the vulnerability of the karst unit. Where caves are encountered, a level of subsurface examination and mapping is also required. The information collected during a KFA is used to prescribe suitable forest practices as outlined in the *Karst Management Handbook for British Columbia* (BC Ministry of Forests, 2001).

Data from reconnaissance-level and/or planning-level karst inventories, along with any other available information on the karst unit, are reviewed during the office stage of a KFA to help direct field activities. The major karst attributes assessed during a KFA include: 1) karst unit boundaries and geological characteristics; 2) the distribution and intensity of surface epikarst development; 3) the overlying soil thickness/texture; 4) the location, type, density and significance of surface karst features; 5) the roughness of the overall karst surface; 6) streams

and hydrology; 7) the potential for caves and other subsurface cavities; and 8) the occurrence of unique or unusual flora/fauna and/or habitat.

The karst vulnerability assessment process at the KFA level is a four-step procedure that determines a vulnerability rating (low, moderate, high, very high) for an identified polygon. The process considers three major criteria: 1) epikarst sensitivity; 2) the density of surface karst features; and 3) subsurface karst potential. The procedure also allows for the integration of three modifying factors: 1) fine-textured, erodible soils; 2) karst roughness; and 3) unique or unusual flora/fauna and/or habitats.

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The Resources Inventory Committee consists of representatives from various ministries and agencies of the Canadian and the British Columbia governments as well as from First Nations peoples. RIC objectives are to develop a common set of standards and procedures for the provincial resources inventories, as recommended by the Forest Resources Commission in its report "The Future of our Forests."

For further information about the Resources Inventory Committee and its various Task Forces, please access the Resources Inventory Committee Website at: http://www.for.gov.bc.ca/ric.

This project was initiated by Gerry Still (Research Branch, Ministry of Forests), and was subsequently managed by Dan Hogan and Steve Chatwin of the Research Branch. The principal contributors to the document were Tim Stokes (Terra Firma Geosciences Services), Paul Griffiths (Cave Management Services), Steve Chatwin (Research Branch, Ministry of Forests), and Bill I'Anson.

Many people assisted directly with the project. Thanks are extended to members of the Karst Management Working Group for their valuable input (in alphabetical order): Hugh Bomford (Canadian Forest Products Ltd.), Peter Bradford (Forest Practices Branch), Cam Brady (Port McNeill Forest District), Charlie Cornfield (Campbell River Forest District), Bob Craven (Western Forest Products Ltd.), Stu Ellis (Canadian Forest Products Ltd.), Gerry Fraser (Western Forests Products Ltd.), Laura Friis (Ministry of Environment, Lands and Parks), Doug Herchmer (Vancouver Forest Region), Dan Hogan (Research Branch), Bill Marshall (Forest Practices Branch), Hal Reveley (Vancouver Forest Region) and Gerry Still (Research Branch).

A number of others also contributed to the document either directly or indirectly during the completion of karst inventory field trials. Thanks to Stephen Flett (Kootenay Lake Forest District), John Pollack (Nelson Forest Region), Matthew Lamb-Yorski (North Coast Forest District), the Chetwynd Division of Canadian Forest Products Ltd., West Fraser Mills Ltd. in Chetwynd, and to Brian Bischoff and Jeff McNally for their assistance in the field.

Thanks must be given to Jim Baichtal of the US Forest Service in the Tongass National Forest, Prince of Wales Island, Southeast Alaska for his illuminating discussions on all aspects of karst and forestry. Thanks also to Tom Aley of the Ozark Underground Laboratory in Missouri for his advice on dye tracing and karst vulnerability; and to Nick Massey of the BC Geological Survey Branch, and Kevin Kiernan with the Forest Practices Board in Tasmania.

Special thanks to Dr. Derek Ford (McMaster University) for lending his expertise to a detailed review of the karst inventory procedures, and for providing his insights and technical knowledge on some of the physical attributes and functions of karst ecosystems.

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1.0 Introduction

1.1 Objectives and Approach

Karst inventory and vulnerability assessment standards and procedures for British Columbia are described in this document. The procedures are based on the recognition that karst terrain is a sensitive and valuable resource that can be highly susceptible to disturbances, such as those associated with timber harvesting and road construction (BC Ministry of Forests, 1997; Stokes and Griffiths, 2000). As a result, the integration of karst management with forest development requires an inventory process that accurately identifies areas of karst terrain and assesses the inherent vulnerability of the karst system.

Three distinct levels for conducting karst inventories and vulnerability assessments are described:

- the reconnaissance-level inventory (typically at 1:250 000 map scale);
- the planning-level inventory and vulnerability potential mapping (typically at 1:20 000 or 1:50 000 map scales[1]); and
- the karst field assessment[2] (KFA) and vulnerability assessment (typically at 1:5000 or 1:10 000 map scales).

These three levels of inventory provide a filtered approach to evaluating karst terrain — beginning at the reconnaissance level and progressing downward through an intermediate planning level and finally to the KFA. Each level has increasing requirements for data collection and evaluation.

The karst inventory and vulnerability assessment process is summarized in Figure 1.1.

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[1] The planning-level inventory procedure was developed and field tested based on a 1:20 000 map scale; however, the same principles and procedures can likely be applied at other appropriate scales, although this has not been field tested.

[2] To conform with Forest Practices Code terminology, a karst inventory completed at the cutblock level (1:5000 or 1:10 000 scales) is referred to as an 'karst field assessment' or a KFA.

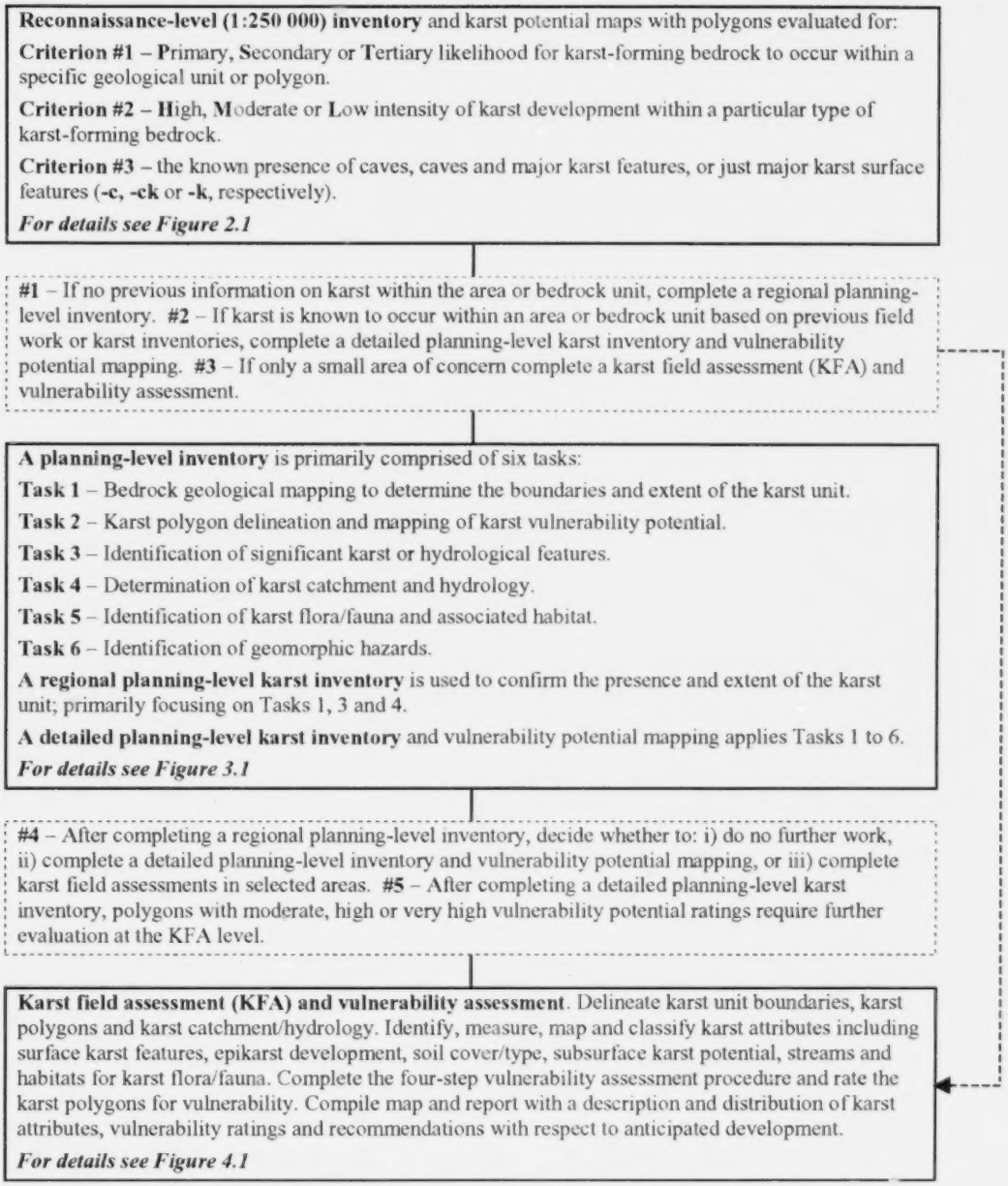
Reconnaissance-level (1:250 000) inventory and karst potential maps with polygons evaluated for:
Criterion #1 – **P**rimary, **S**econdary or **T**ertiary likelihood for karst-forming bedrock to occur within a specific geological unit or polygon.
Criterion #2 – **H**igh, **M**oderate or **L**ow intensity of karst development within a particular type of karst-forming bedrock.
Criterion #3 – the known presence of caves, caves and major karst features, or just major karst surface features (**-c, -ck** or **-k**, respectively).
For details see Figure 2.1
#1 – If no previous information on karst within the area or bedrock unit, complete a regional planning-level inventory. **#2** – If karst is known to occur within an area or bedrock unit based on previous field work or karst inventories, complete a detailed planning-level karst inventory and vulnerability potential mapping. **#3** – If only a small area of concern complete a karst field assessment (KFA) and vulnerability assessment.
A planning-level inventory is primarily comprised of six tasks:
Task 1 – Bedrock geological mapping to determine the boundaries and extent of the karst unit.
Task 2 – Karst polygon delineation and mapping of karst vulnerability potential.
Task 3 – Identification of significant karst or hydrological features.
Task 4 – Determination of karst catchment and hydrology.
Task 5 – Identification of karst flora/fauna and associated habitat.
Task 6 – Identification of geomorphic hazards.
A regional planning-level karst inventory is used to confirm the presence and extent of the karst unit; primarily focusing on Tasks 1, 3 and 4.
A detailed planning-level karst inventory and vulnerability potential mapping applies Tasks 1 to 6.
For details see Figure 3.1
#4 – After completing a regional planning-level inventory, decide whether to: i) do no further work, ii) complete a detailed planning-level inventory and vulnerability potential mapping, or iii) complete karst field assessments in selected areas. **#5** – After completing a detailed planning-level karst inventory, polygons with moderate, high or very high vulnerability potential ratings require further evaluation at the KFA level.
Karst field assessment (KFA) and vulnerability assessment. Delineate karst unit boundaries, karst polygons and karst catchment/hydrology. Identify, measure, map and classify karst attributes including surface karst features, epikarst development, soil cover/type, subsurface karst potential, streams and habitats for karst flora/fauna. Complete the four-step vulnerability assessment procedure and rate the karst polygons for vulnerability. Compile map and report with a description and distribution of karst attributes, vulnerability ratings and recommendations with respect to anticipated development.
For details see Figure 4.1

Figure 1.1. Summary of karst inventory standards and vulnerability assessment procedures for BC.

Karst vulnerability methodologies can be applied at both the planning level and the KFA. The goals of these methodologies are to analyze data from the respective inventory levels and stratify the karst landscape (including its subsurface component) into polygons of similar karst vulnerability.[3] At the planning level, karst mapping is carried out whereby polygons are drawn and rated for karst vulnerability potential.[4] These polygons highlight the most dominant karst vulnerability potential ratings (low, moderate, high or very high) within the polygon. Information on karst vulnerability potential at the planning level is used for both resource planning and to direct further inventory work.

At the KFA level, detailed karst vulnerability assessments are carried out using a four-step procedure. Once again, four qualitative karst vulnerability ratings can be determined—low, moderate, high and very high. However, the polygons are smaller and more refined (due to more field checking) than at the planning level. The vulnerability ratings at the KFA level are used to guide forest harvesting and road construction prescriptions, as outlined in the draft *Karst Management Handbook for British Columbia* (BC Ministry of Forests, 2001).

A fundamental concept underlying the karst inventory and vulnerability assessment process is that the karst landscape be treated as a three-dimensional system, as opposed to a collection of discrete surface features that may, or may not, be connected to subsurface openings or caves. This system approach recognizes that karst operates as a holistic unit, whereby changes to conditions at the surface can influence conditions below the surface (e.g., heavy rainfall at the surface can lead to subsurface flooding). The connectivity or openness of a karst system is a critical factor controlling the degree and speed of changes that can occur between various components of the system (e.g., water or air transfer between the surface and subsurface).

In a broader sense, this system approach is also intended to include all components of the karst ecosystem,[5] with not only its distinct geological, geomorphological and hydrological characteristics, but also (as much as practically possible) other attributes, such as karst biota and air exchange. Most of the karst inventory and vulnerability assessment procedures outlined in this document are applied at the surface of the karst system; however, the subsurface component of karst is also considered. Where caves or other underground cavities are encountered, subsurface investigation and mapping is required to determine their significance and orientation with respect to the surface. This information is then used in the application of specific surface management prescriptions.

Much of the work used to develop the procedures in this document is based on a technical report titled *A Preliminary Discussion of Karst Inventory Systems and Principles (KISP) for British Columbia* (Stokes and Griffiths, 2000). Testing of the proposed karst inventory and vulnerability assessment methodologies outlined in the KISP document began in 1999 when digital reconnaissance-level (1:250 000 scale) karst potential maps for the entire province of British Columbia were generated (Stokes, 1999). During 1999 and 2000, karst inventory field trials were carried out at the planning and KFA levels to test and refine the proposed

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[3] Karst vulnerability is defined as 'the susceptibility of a karst ecosystem to change, and is considered to be a function of its inherent characteristics and sensitivity.'

[4] Karst vulnerability potential is defined as 'the likelihood for a particular vulnerability rating to occur within a specific planning-level polygon' (e.g., a planning-level polygon with a moderate vulnerability potential would likely include predominately moderate vulnerability areas with lesser amounts of low or high).

[5] A karst ecosystem is defined as 'a functional unit consisting of all living and non-living physical and chemical elements of the karst environment that are linked through nutrient cycling and energy flow.'

methodologies. The field trials were held at five sites—two on Vancouver Island (Extravagant Creek and Tashish River), two on the mainland (Chetwynd area and Cody Caves), and one on the North Coast (Chapple Inlet).

1.2 Karst Processes

Karst is a distinctive topography resulting from geological weathering and erosional processes. The primary process is the dissolving action of water on soluble bedrock (usually limestone, dolomite, marble and, to a lesser extent, gypsum) which produces a landscape characterized by features such as epikarst, vertical shafts, sinkholes, sinking streams, springs, complex subsurface drainage systems and caves. The unique features associated with karst landscapes result from a complex interplay between geology, climate, topography, hydrology and biological factors over long time scales. Further details on karst-forming processes can be found in a number of well-recognized scientific texts, such as Ford and Williams (1989), White (1988), and Jennings (1985). General issues related to the sensitivity of karst can be found in White et al. (1995), Kiernan (1990), and Harding and Ford (1993). In British Columbia, more recent work on forested karst terrain includes studies by Stokes (1996), Blackwell (1995), Stokes and Griffiths (2000), and Chatwin (1999).

1.3 Distribution of Karst in British Columbia

Karst is known in all six of British Columbia's forest regions, but has only been well documented in a limited number of locations (e.g., Vancouver Island). Carbonate bedrock underlies approximately 10% of British Columbia and provides an extensive area for potential karst development. The level of karst development across the province is highly variable due to the great range of bedrock types, physiography and biogeoclimatic settings. However, some generalizations and comparisons can be made to other parts of the world so that the overall significance of British Columbia's karst can be considered.

Much of the karst in British Columbia has developed in mountainous terrain with high rainfall and hydraulic heads that allow for extensive recharge and discharge of waters. Glaciation has played a major role in exposing, eroding and burying earlier developed karst. Extensive areas of carbonate in alpine karst areas occur along the Rocky Mountains, particularly at the southern end. These are similar to the well-studied tracts of karst in the European Alps and the Pyrenees. Well-developed karst areas associated with temperate rainforest occur in the significant carbonate units of Vancouver Island, and in smaller areas along the North Coast (e.g., Chapple Inlet) and in the Queen Charlotte Islands. These temperate rainforest karst areas are comparable to those found in New Zealand, Tasmania and Chile. Karst associated with Interior forests in the Purcell Mountains (e.g., Cody Caves and Namiku Caves) form steep and narrow bands that have similarities to the 'stripe karst' of northern Norway. Less well-known areas of karst are reported in northwest British Columbia (e.g., along the Stikine and Taku Rivers) and in northeast British Columbia (e.g., near Chetwynd and Prince George). Karst in the Interior Plateau (e.g., near Williams Lake) is the least known, and could be equivalent to that found in the foothills of the Slovenian Alps. Extensive glacial materials found in the Interior likely mask significant areas of karst terrain, with the karst only apparent where the carbonate units are exposed in alpine or subalpine locations. The distribution of karst in British Columbia is further detailed in the reports of Stokes and Griffiths (2000) and Stokes (1999).

2.0 Reconnaissance-level Karst Potential Mapping and Inventory

The purpose of reconnaissance-level karst potential[6] maps is to flag areas of likely karst development to assist with strategic planning (e.g., higher level plans, land use plans, TFL management plans), and to direct more detailed karst inventories where required. Reconnaissance-level (1:250 000 scale) karst potential maps covering all of British Columbia were produced in 1999 (Stokes, 1999). The project was an office-based exercise that included an analysis of 1:250 000 digital bedrock geology data (the BC Geological Survey and the Geological Survey of Canada), and information on known cave and karst occurrences in British Columbia. Approximately 7568 polygons were evaluated for karst potential, covering 87 NTS map sheets (1:250 000 scale).

Two criteria were used to evaluate karst potential within a particular polygon. Criterion #1, the likelihood of karst forming or soluble bedrock (e.g., limestone, dolomite or gypsum) occurring within a unit (or map polygon), was evaluated by estimating the proportion of soluble bedrock and rating it as one of three categories—Primary (P) >50%, Secondary (S) 20–49% or Tertiary (T) 5–19%. Criterion #2, the intensity of karst development in a particular type of soluble bedrock, was determined for each map polygon using four principal attributes that are important controlling factors for karst development—chemical purity, bedrock lithology, topographic position and unit thickness/continuity.[7] Data for each of these attributes were obtained, categorized and placed into a numerical algorithm, which weighted the attributes from the most important (chemical purity) to the least important (unit thickness/continuity). Numerical values from the algorithm were then qualitatively ranked as high (H), moderate (M) or low (L) for their intensity of karst development. A third criterion —Criterion #3—the known occurrence of caves or major surface karst features,[8] was also included on the karst potential maps. However, subsequent evaluation of this procedure indicated that Criterion #3 data should not be directly included in the karst potential maps, but rather used as a separate layer in the mapping system (see Stokes, 1999).

The methodology used to compile the reconnaissance-level karst potential maps is summarized in Figure 2.1.

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[6] The concept of 'karst potential' is used to provide an indication of where karst might occur and what level of karst development might be anticipated.

[7] There are other important factors that control karst development (e.g., secondary porosity). However, this information was not available at the scale of mapping and/or level of data collection.

[8] Major surface karst features can be considered as any single, large feature or recognizable group of meso-scale karst features (such as sinkholes, swallets, karst bridges, karst canyons or cave entrances). It is not intended for micro- or small-scale solution runnels or fractures apparent on individual outcrops.

Generation of reconnaissance-level karst potential polygons from 1:250 000 digital bedrock data from the BC Geological Survey and the Geological Survey of Canada.

Evaluation of each karst potential polygon for:

Criterion #1 – the likelihood of karst-forming bedrock to occur within a specific geological unit or polygon.

Criterion #2 – the intensity of karst development within a particular type of karst-forming bedrock.

Criterion #3 – the known presence of caves or major karst features.

Criterion #1 – based on an estimate of the percentage of soluble bedrock within a unit.

Primary (P): >50% soluble bedrock, **Secondary** (S): 20–49% soluble bedrock, and

Tertiary (T): 5–19% soluble bedrock.

Criterion #2 – determined from a weighted numerical algorithm that includes four primary attributes related to karst development: chemical purity (P), bedrock lithology (BL), topographic position (TP) and unit thickness/continuity (UT). Each map polygon is given a numerical rating from 1 to 5 for each of the primary attributes.

$$\text{Criterion \#2} = (4 \times \text{P}) + (3 \times \text{BL}) + (2 \times \text{TP}) + (\text{UT})$$

From the numerical values, qualitative ratings of High (H), Moderate (M) and Low (L) are derived for likely intensity of karst development, whereby High is >40, Moderate is 25–39 and Low is <24.

Criterion #3 – the confirmed presence of caves or major karst features is used to highlight areas of known karst development.

Final product: 1:250 000 maps with shaded polygons for Criterion #1 (P, S, or T) and Criterion #2 (H, M or L) and labelled c, -ck and -k, for known caves, known caves/major karst features, and known major karst features. Note: it is recommended that known cave/karst features be separated from the karst potential mapping information.

Prior to determining specific planning-level or karst field assessment (KFA) requirements for a site using the karst potential maps, some form of on-site karst information is required, either from field work or previous karst inventories. Karst potential maps provide an indication as to the likely extent of karst units and the possible intensity of karst development, but have some significant limitations and should be used with caution.

No previous information on karst within the area/bedrock unit. Complete a regional planning-level inventory to confirm the presence and extent of karst. *See Figure 3.1.*

Karst known to occur within the area/bedrock unit from previous field work or karst inventories. Complete a detailed planning-level karst inventory and vulnerability potential mapping, or, if only a small area of interest, complete a karst field assessment (KFA) and vulnerability assessment. *See Figure 3.1.*

Figure 2.1. Methodology used to compile reconnaissance-level (1:250 000 scale) karst potential maps and inventory data for BC, with links to the planning-level inventory and the karst field assessment.

Prior to the initiation of any karst inventory work in a particular area, it is recommended that the reconnaissance-level karst potential maps and inventory data be examined. These maps are available in Arc-Info format and can be readily incorporated into any GIS system. The Arc-Info format provides boundaries for the karst potential polygons and is linked to a database with karst attribute and rating information. Spreadsheets for the karst attribute and rating data are available in Excel (.xls) format, and can be linked to hard copy maps derived from plot files. The Arc-Info files, Excel spreadsheets and plot files are available through the Ministry of Forests, Research Branch, in Victoria (http://www.for.gov.bc.ca/ftp/Branches/Research/external/!publish/karst/). The information also includes a report covering the scope, methodologies, limitations and findings of the project (see Stokes, 1999).

An evaluation of the reconnaissance-level karst potential maps was carried out during the karst inventory field trials. During the field trials, it was apparent that the karst potential maps had varied success in their ability to accurately portray the level of karst development in different areas. Where the unit was known to contain karst from previous field work (e.g., the Quatsino Formation of Vancouver Island), the Criteria #1 and #2 data were generally reliable. Where little to no field information was available on the bedrock unit (e.g., the Palliser Formation of the Rocky Mountains), the ratings, particularly Criterion #2, were less precise. However, one advantage of the karst potential maps is that once a unit has been examined in the field, it is then possible to cautiously extrapolate ratings to adjacent areas. Overall, the karst potential maps provide a useful preliminary tool in the initial stages of karst evaluation; however, they have some severe limitations and should be treated accordingly. Continual updating and refinement of these maps is essential if they are to be used successfully.

The main limitations of the reconnaissance-level karst potential maps are:

- the Criteria #1 and #2 ratings can be unreliable in areas not field checked for karst;
- karst can occur outside the indicated polygons (e.g., as small lenses/pods or in thinly bedded units with striped karst; pers. com. Ford, 1999);
- the 1:250 000 polygon boundaries are not reliable at more detailed scales; and
- not all known cave/karst information was included on the maps due to time/cost limitations for the project (see Stokes, 1999).

The karst inventory field trials highlighted a number of refinements that could be incorporated into the reconnaissance-level karst potential mapping. These refinements include:

- separating out the known cave and karst information;
- modifying the Criterion #2 rating to consider the broad physiographic regions, biogeoclimatic zones and glacial cover in British Columbia;
- altering the Criterion #1 categories to highlight only carbonate units that have >80% soluble bedrock; and
- resolving inconsistencies in the original bedrock data for certain map sheets.

Overall, the reconnaissance-level karst potential maps can be considered a good starting point as background information prior to completing planning-level inventories or KFAs. The Criteria #1 and #2 ratings provide a general idea as to what might be anticipated for a soluble bedrock unit or map polygon, but these ratings can, in practice, be one or possibly even two categories out. Field checking or prior knowledge of karst conditions at a site is crucial to help determine the requirement for planning-level inventories or KFAs.

3.0 Planning-level Karst Inventory

3.1 Goals, Objectives and Approach

The primary goals of the planning-level karst inventory are to provide data for mapping karst vulnerability potential, and to assist with landscape-level planning at the 1:20 000 or 1:50 000 scale. This may require a significant amount of field checking.

The principal objectives of the planning-level inventory are to:

- delineate the geological boundaries of the karst unit and its three-dimensional distribution;
- determine the regional extent of the karst catchment;[9]
- locate and identify major surface karst features, cave entrances and evidence of epikarst development;
- consider the potential for subsurface openings;
- define karst polygons and rate them for karst vulnerability potential;
- identify the likely presence of any unique karst-specific biota or related habitat; and
- identify any geomorphic hazards that could potentially impact the karst unit.

Initiation of a planning-level inventory should occur under the following circumstances:

- reconnaissance-level karst potential maps indicate that the area proposed for development may be underlain by karst;
- there is previous knowledge of karst in or around an area of proposed development; or
- karst features are identified in or around an area of proposed development.

There are two types of planning-level inventory, depending on how much is known about the karst in the area of interest:

1) Regional planning-level inventory – A regional planning-level inventory would typically be carried out in areas where little to no prior knowledge of karst development is available. However, karst may be suspected from either unconfirmed field reports or reconnaissance-level karst potential maps. The main objective of a regional planning-level inventory is to evaluate the presence and extent of karst within an area (or bedrock unit) to help determine the need for any further inventory work. A regional planning-level inventory would focus primarily on Tasks 1, 3 and 4 as outlined under Section 3.3.

2) Detailed planning-level inventory – A detailed planning-level inventory is used to evaluate areas of karst that are either known or anticipated. One of the primary objectives of a detailed planning-level inventory is to stratify the karst landscape into polygons of different vulnerability potential. A detailed planning-level inventory would include all of Tasks 1 to 6 as outlined under Section 3.3.

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[9] A karst catchment differs from a topographic catchment in that it can include cross-divide connections through subsurface drainage paths.

Prior to initiating any planning-level inventory work, the decision must be made as to whether to conduct a regional or detailed planning-level inventory based on previous knowledge and/or experience with karst conditions in the area of interest (see Figure 3.1 for a summary of the planning-level methodology). If the decision is made to conduct a regional planning-level inventory, there are three possible outcomes regarding the requirement for further inventory work:

1. no additional karst inventory is required for the area;
2. a detailed planning-level karst inventory is required for all or part of the area; or
3. a KFA is required for specific parts of the area (see Section 4.0).

One or more combinations of these options could be employed, depending on the size and complexity of the karst unit. The decision whether further inventory work is required or not should consider the anticipated activities in the area. For example, if a series of roads and cutblocks are anticipated over a large, well-developed karst unit, a detailed planning-level inventory would likely be warranted. However, if only one cutblock is planned near a small karst unit, it may be appropriate to go directly to a KFA, rather than completing a detailed planning-level inventory.

3.2 Initial Office Work and Data Compilation

As a first step in completing a regional or detailed planning-level inventory, all available information for the area of interest is collected and compiled, and a series of working maps developed. An example of existing information that should be gathered includes:

- detailed bedrock geology maps (1:50 000 scale or less);
- surficial geology maps (1:50 000 scale or less);
- detailed topographic information (1:50 000 and 1:20 000);
- air photos (both recent and historical, colour and/or black and white);
- satellite imagery data or other remote sensing information, if available;
- terrain stability mapping (1:20 000);
- karst inventory maps and reports, cave maps and related information, forest cover maps, forest development plans;
- recreation maps with K00 (or L5) polygon designations;
- terrestrial ecosystem and fish inventory maps; and
- BC Environment records on any unique karst-related biota or habitat.

All relevant karst information (e.g., unit boundaries, identified features) is transferred onto a base map. This base map is usually a digital TRIM map and would generally display contours, streams, coastlines and lakes. Geological boundaries for the karst units are taken from detailed (1:50 000 scale or less) bedrock maps and plotted with the appropriate line work (e.g., solid line for defined, dashed for approximate and dotted for assumed.) (Directly transferring polygon boundaries from the 1:250 000 reconnaissance-level karst potential maps to the 1:20 000 maps should be avoided where possible because of likely errors due to differences in scale.) Data for karst polygon boundaries can also be obtained from recreation, terrain or other maps, but may be of varying reliability.

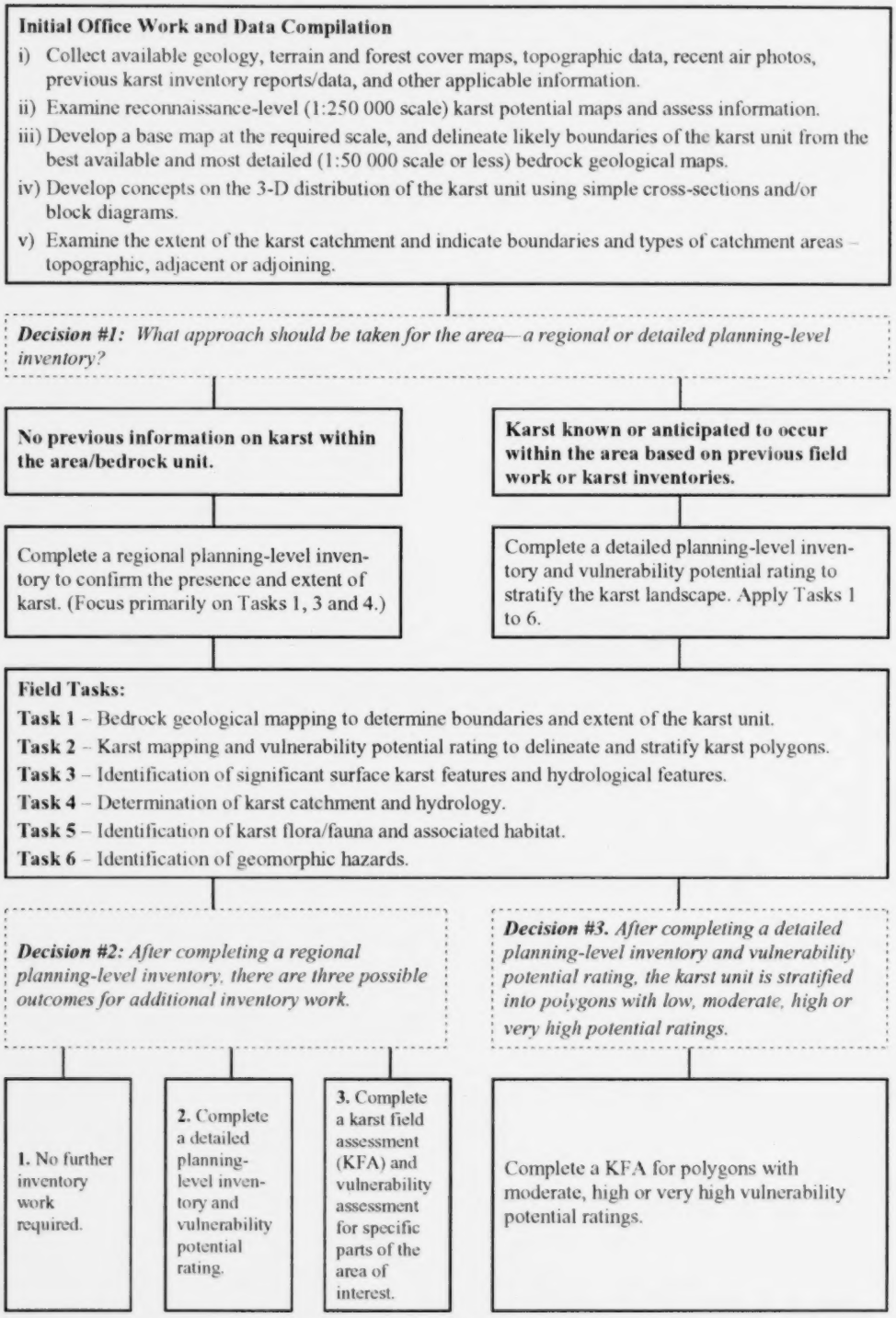
Initial Office Work and Data Compilation
i) Collect available geology, terrain and forest cover maps, topographic data, recent air photos, previous karst inventory reports/data, and other applicable information.
ii) Examine reconnaissance-level (1:250 000 scale) karst potential maps and assess information.
iii) Develop a base map at the required scale, and delineate likely boundaries of the karst unit from the best available and most detailed (1:50 000 scale or less) bedrock geological maps.
iv) Develop concepts on the 3-D distribution of the karst unit using simple cross-sections and/or block diagrams.
v) Examine the extent of the karst catchment and indicate boundaries and types of catchment areas – topographic, adjacent or adjoining.
Decision #1: What approach should be taken for the area—a regional or detailed planning-level inventory?
No previous information on karst within the area/bedrock unit.
Karst known or anticipated to occur within the area based on previous field work or karst inventories.
Complete a regional planning-level inventory to confirm the presence and extent of karst. (Focus primarily on Tasks 1, 3 and 4.)
Complete a detailed planning-level inventory and vulnerability potential rating to stratify the karst landscape. Apply Tasks 1 to 6.
Field Tasks:
Task 1 – Bedrock geological mapping to determine boundaries and extent of the karst unit.
Task 2 – Karst mapping and vulnerability potential rating to delineate and stratify karst polygons.
Task 3 – Identification of significant surface karst features and hydrological features.
Task 4 – Determination of karst catchment and hydrology.
Task 5 – Identification of karst flora/fauna and associated habitat.
Task 6 – Identification of geomorphic hazards.
Decision #2: After completing a regional planning-level inventory, there are three possible outcomes for additional inventory work.
Decision #3. After completing a detailed planning-level inventory and vulnerability potential rating, the karst unit is stratified into polygons with low, moderate, high or very high potential ratings.
1. No further inventory work required.
2. Complete a detailed planning-level inventory and vulnerability potential rating.
3. Complete a karst field assessment (KFA) and vulnerability assessment for specific parts of the area of interest.
Complete a KFA for polygons with moderate, high or very high vulnerability potential ratings.

Figure 3.1. Methodology for the planning-level karst inventory.

Detailed bedrock geology maps (1:50 000 scale or less) can be used to determine the likely three-dimensional distribution of karst units by applying basic geological knowledge on bedrock lithology types and structure (e.g., bedding dip, folds and faults). Simple geological cross-sections can be constructed across the area of interest or more complex block models can be developed. Knowing the three-dimensional distribution of the karst unit and dominant structural controls can greatly assist in understanding the likely extent of the karst hydrological system and the orientation of cave passages and subsurface conduits (e.g., preferential development of a cave system along bedding planes).

Initial indications on the regional extent of the karst catchment are obtained from information on the distribution of the karst unit, topographic maps, and any known karst features. The limits of the karst unit of interest and any nearby karst units are plotted onto the base map along with lines indicating the topographic catchment divides. Upslope karst and non-karst terrain within the same topographic catchment that contributes water to the karst unit of interest is part of the karst catchment and is termed the 'adjacent karst catchment.' Because of the subsurface flow characteristics of karst, contiguous karst units in different topographic catchments, along with their respective upslope non-karst catchments, can also contribute water to the karst unit of interest. These are termed 'adjoining karst catchments.' The limits of the various karst catchment types are drawn on the base maps and indicated as to whether they are topographic, adjacent or possibly adjoining (see Figure 3.2). This information will provide the first step in determining what are the likely issues of concern with respect to the karst hydrological system, and may also provide some indication as to whether dye tracing is required to help determine subsurface flow patterns (see Section 3.3.4). Where large karst catchments are present, 1:50 000 scale base maps may be useful.

Any previous information on likely unique or unusual flora, fauna or habitats within a karst area of interest should be compiled for the project area. Initial information might be obtained from existing inventory reports or government agencies (e.g., Ministry of Environment, Lands and Parks, Conservation Data Centre). Details on likely fauna and flora habitats associated with karst are discussed in Section 3.3.5. A list of karst flora and fauna species, with particular emphasis on British Columbia, is provided in Tables A1 and A2 in Appendix A.

Satellite imagery data could be used at the planning level to assist with the mapping procedures. At present, coloured or black and white IRS satellite imagery data are available with a resolution of 5 m pixels, and can be plotted on maps with good clarity at scales up to 1:20 000. The more recent IKONOS satellite (launched in 1999) can provide data with a resolution of 1 m pixels, and can be plotted on maps up to 1:2500 scale (McLaughlin, pers. com., 1999). The main advantage of the satellite imagery data is that it can readily provide current information for a site. Other advantages of satellite imagery data, compared to air photos, are that it is less expensive and available by the map sheet. Satellite imagery also has the potential for identifying karst units by enhancing various colour bandwidths to highlight changes in vegetation or site conditions. This approach has not been tested in the forested karst areas of British Columbia, but is worthy of consideration.

Light detection and ranging (LIDAR) has recently been used successfully in southeast Alaska to accurately map karst features through the forest canopy (J. Baichtal, pers. com., 2000).

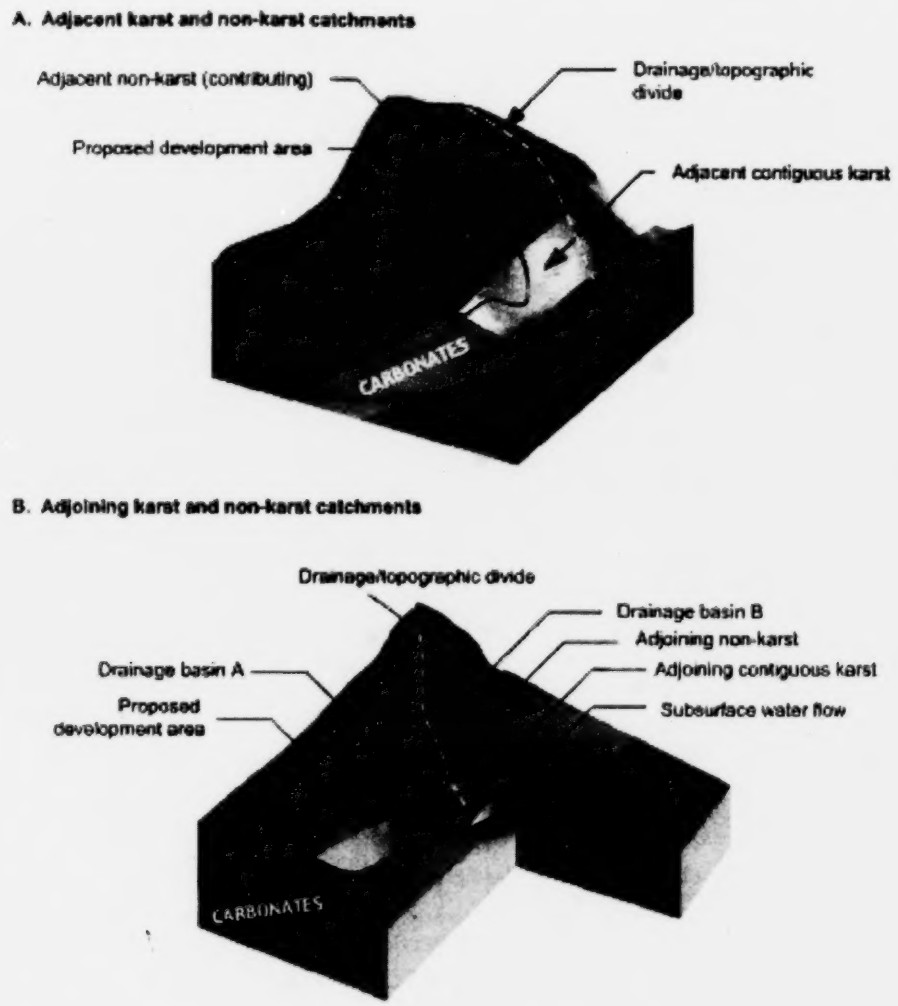

Figure 3.2. Karst catchment hydrology and definitions.

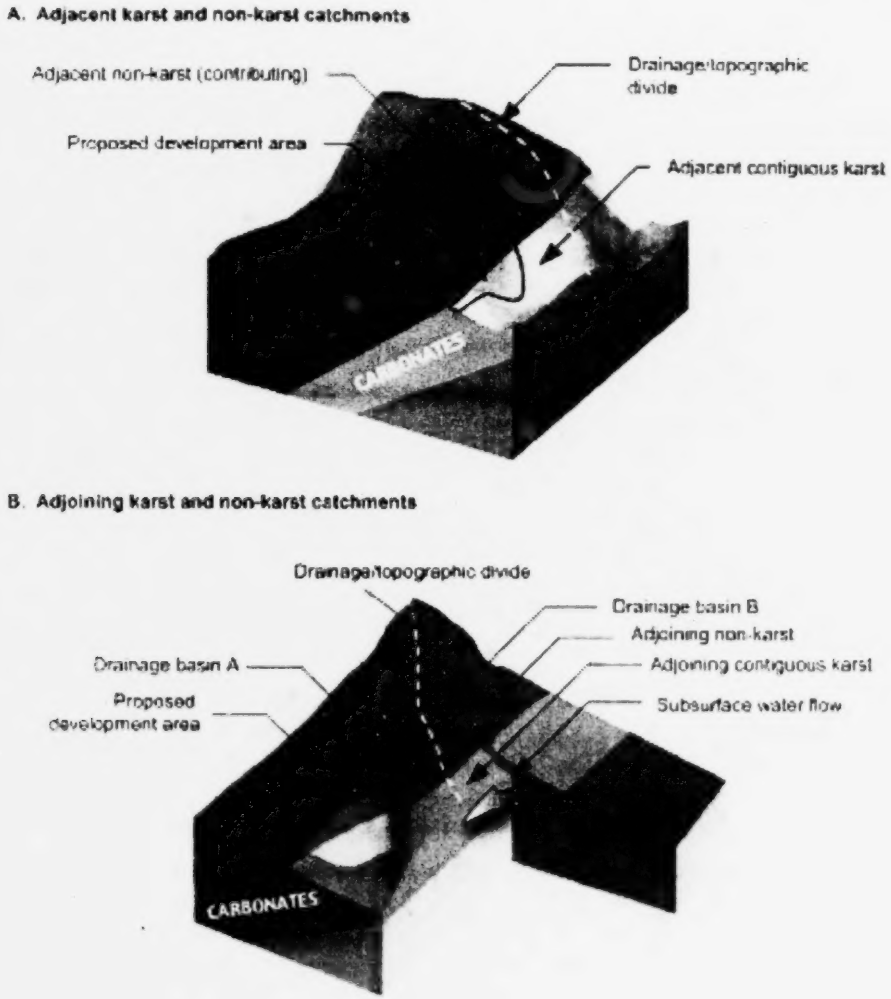

Figure 3.2. Karst catchment hydrology and definitions.

3.3 Required Field Work and Tasks

The key attributes to be located, identified and measured during a planning-level inventory are provided in Appendix B.

Field work for the planning-level inventory can be divided into six tasks:

Task 1 – bedrock geological mapping;

Task 2 – karst mapping and evaluation for vulnerability potential;

Task 3 – identification of significant surface karst and hydrological features;

Task 4 – evaluation of the karst catchment for the area of interest;

Task 5 – identification of karst flora and fauna, and associated habitats; and

Task 6 – identification of geomorphic hazards.

The amount of work required for each of these tasks in any particular area is highly variable, and depends on site conditions and the amount of existing information. For example, if detailed bedrock geology maps and previous surface karst feature data are available for a site, Tasks 1 and 3 would likely be reduced. However, if the only available bedrock geology maps are at 1:250 000 scale, bedrock mapping could form a major part of the work. Overall, Tasks 1, 2 and 3 are anticipated to be the principal tasks requiring most of the field time.

3.3.1 Task 1 – Bedrock Geological Mapping

Bedrock mapping is an integral and fundamental part of the planning-level inventory, as it entails determining the boundaries and extent of the karst unit. Where complex geological relationships are encountered, or where detailed bedrock mapping is unavailable, considerable field work may be required. Less bedrock mapping is required where the geology is relatively straightforward or where previous detailed mapping is available. Bedrock geological mapping should closely follow procedures outlined in *Specifications and Guidelines for Bedrock Mapping in British Columbia* (RIC, 1996). However, in many cases, detailed bedrock mapping and interpretation of the bedrock geology to standards required by the provincial government (e.g., BC Geological Survey) are not likely to be achieved, primarily due to time limitations in the field.

In general, bedrock mapping should focus on:

- determining the locations and types of geological contacts and relationships;
- the types and changes in bedrock lithology; and
- the main bedrock fault and fold structures.

Sufficient bedrock information should be obtained so that the surface and likely three-dimensional extent of the main karst-forming unit can be determined.

3.3.2 Task 2 – Karst Mapping and Vulnerability Potential

Karst mapping and evaluating vulnerability potential is one of the major tasks to be completed during a detailed planning-level inventory. This task involves the delineation of karst polygons, the collection of data on karst characteristics and an evaluation of vulnerability potential. The purpose of this mapping procedure is primarily to stratify the karst landscape into polygons with similar karst attributes and characteristics. Many of the procedures and standards used for karst mapping are similar to those for terrain mapping (RIC, 1996; Howes and Kenk, 1988; and Ministry of Forests, 1995). However, the fundamental concepts of karst mapping are based, as much as possible, on the distribution and variations of karst characteristics, rather than those of terrain. While many of the

attributes considered for karst mapping are similar to those required for terrain mapping (e.g., surficial cover type/thickness, slope gradient, drainage), additional attributes specifically related to karst processes need to be collected, including information on epikarst development, surface karst feature density and subsurface karst potential.

Preliminary Karst Polygon Delineation

Prior to field work for karst mapping, the typing of suitable air photos[10] is used to delineate the boundaries for preliminary karst polygons. Many of the procedures for the selection, use and interpretation of air photos are similar to those outlined in *Guidelines and Standards for Terrain Mapping in British Columbia* (RIC, 1996); likewise for the methods of defining polygons, delimiting polygon boundaries and the usage of feature symbols. The geological boundaries of the anticipated karst units are transferred from available bedrock geology maps to the air photos as accurately as possible, followed by boundaries for the preliminary karst polygons. Successful boundary delineation of karst polygons from air photos can vary depending on the experience of the mapper, the presence of vegetation cover, and the intensity of karst development. Air photo interpretation of karst characteristics in lightly forested areas (e.g., subalpine slopes) and previously harvested sites is generally easier than in the denser canopies of coastal or interior forested karst. However, with careful stereoscopic examination, large surface karst features, disrupted drainage patterns and changes in surface texture are commonly visible even within denser canopy areas. In previously harvested areas, historic air photos can be particularly useful, as the karst is more easily recognized before tree height and canopy closure obscures the ground surface.

The method for delineating karst polygons is somewhat similar to that of terrain polygons, whereby a specific area is delimited with similar processes and characteristics. Typically, terrain or karst polygons define a homogenous area with respect to adjacent polygons, and can be either simple, with one controlling attribute, or composite, with two or more controlling attributes. The best approach at a previously unknown site is to initially use terrain characteristics to develop preliminary karst polygon boundaries. However, as field work progresses, and additional data on karst attributes is collected, the polygon boundaries can be altered or modified to reflect the new information. A mapper familiar with karst processes should be able to rely on past knowledge of similar sites, and, in effect, develop karst analogue models based on the characteristics of the landscape. For example, in limestone of the Quatsino Formation of Vancouver Island, gentle moderate slope benches are more likely to contain surface karst features than steep slopes. Preliminary karst polygons can initially be quite large, but are generally sub-divided one or more times during subsequent field work.

Field Work Methodologies and Collection of Karst Data

In general, field work methodologies for karst mapping are similar to that for terrain mapping (refer to Section 7.0 in the *Guidelines and Standards for Terrain Mapping in British Columbia*). However, there are differences in the intensity of field checking, types of data collected and the ways in which it is compiled. These differences and refinements are outlined below.

Karst processes and features have been categorized to a limited extent in the *Terrain Classification System for British Columbia* (RIC, 1997), with a code for the karst process (-K) and a number of on-site symbols for certain karst features (e.g., sinkholes). However,

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[10] Either colour or black and white air photos are acceptable; however, newer photos are better so that recent features (e.g., forest roads/cutblocks) can be used for field orientation.

karst data collection procedures required for karst mapping are much more detailed. Codes have been developed for epikarst development, surface karst feature density, subsurface karst potential, and bedrock type/proportion. A number of other additions/refinements have been made, such as codes for surficial material thickness, karst micro-topography and on-site mapping symbols. Table 3.1 outlines headings in a data file that can be used in a spreadsheet to assist in the gathering of information, while Table 3.2 provides descriptions and categories for karst attribute data collected during field work. Karst mapping could, if desired, eventually be integrated into the *Terrain Classification System for British Columbia* (RIC, 1997); however, for the present, it is suggested that it be kept as a stand-alone procedure until it has been further tested and applied in the field.

Table 3.1. Descriptions of data file headings used for karst mapping and vulnerability potential ratings

Polygon #	Number of polygon corresponding to map sheet.
Soluble Bedrock Unit	Name of soluble bedrock unit. Useful if more than one unit on map sheet.
Bedrock Type and Proportion of Soluble Bedrock in Polygon	Type of soluble bedrock and proportion anticipated in the polygon (see Table 3.2). For example, lsX-4 would indicate 50–80% limestone anticipated within the polygon.
Soluble Bedrock Confirmed in Outcrop	A Yes or No response as to whether soluble bedrock was encountered in the polygon during field work.
Surficial Material Type/Thickness	Use code as in *Terrain Classification System for BC*, except for addition indicated in Table 3.2.
Qualifying Descriptor	As in *Terrain Classification System for BC*, but could be used for karst micro-topography code in Table 3.3.
Geologic Processes	Use code as in *Terrain Classification System for BC*.
Slope Gradient/Class	Use code as in *Terrain Classification System for BC*.
Drainage	Use code as in *Terrain Classification System for BC*.
Epikarst Development	Use code as in Table 3.2.
Surface Karst Feature Density	Use code as in Table 3.2.
Subsurface Karst Potential	Use code as in Table 3.2.
Vulnerability Potential Rating	Overall vulnerability potential ratings are provided for each polygon based on a qualitative evaluation of karst and terrain characteristics. These ratings are: L – low, M – moderate, H – High and V – Very High.
Level of Field Evaluation	A rating is provided for each polygon to provide an indication as to the level of field examination carried out.
	L – low: polygon not traversed; attributes determined from adjacent polygons and/or air photos, etc.
	M – moderate: polygon traversed once.
	H – high: polygon traversed at least twice.
Comments	Any relevant comments that relate to the polygon. Could include comments on possible biota sites or significant surface karst features.

Table 3.2. Planning-level karst mapping attributes and descriptions

Bedrock Type and Proportion of Soluble Bedrock in Polygon
ls – limestone, g – gypsum, d – dolomite
X-1 – <10% soluble bedrock in polygon
X-2 – 10–20% soluble bedrock in polygon
X-3 – 20–50% soluble bedrock in polygon
X-4 – 50–80% soluble bedrock in polygon
X-5 – >80% soluble bedrock in polygon
Surficial Material Type and Texture as in the *Terrain Classification System for BC* (TCS-BC). (Note: apply symbol 'O' for organic forest litter and descriptors for organic texture, regardless of depth, as this typically overlies well-developed karst surfaces.)
Qualifying Descriptors as in the TCS-BC, could add descriptions for karst micro-topography
Drainage, Slope Class and Geological Processes as in TCS-BC
Surficial Material Thickness (slightly modified from the TCS-BC)
x – very thin >2 cm < 20 cm and frequent bedrock outcrops
s – shallow veneer 20-50 cm with common bedrock outcrops
v – veneer 50-100 cm with a few outcrops
b – blanket 100-200 cm and rare outcrops
t – thick blanket >200 cm and no outcrops
Epikarst Development
u – Unknown epikarst development Epikarst surface not visible or buried by thick surficial materials.
n – No apparent epikarst development No observed solutional epikarst development on confirmed carbonate bedrock
s – Slightly developed epikarst Widely spaced (>2 m) solutional openings, less than an average of 0.5 m depth.
m – Moderately developed epikarst Medium spaced (<1 m) solutional openings with an average of 0.5–1.0 m depth.
h – Highly developed epikarst Closely spaced (<0.5 m) solutional openings with an average 1–2 m depth.
i – Intensely developed epikarst Very closely spaced (<0.25 m) solutional openings typically >2 m depth.
Surface Karst Feature Density (Mesoscale dimensions >2 m and <20 m in size).
N – No karst features observed or anticipated on surface No karst features due to absence of karst processes or mantling by thick soil deposits.
L – Low density of karst features Few sinkholes, grikes and cave entrances/shafts (1–5 features/ha).
M – Moderate density of karst features Occasional sinkholes, grikes and cave entrances/shafts (5–10 features/ha).
H – High density of karst features Numerous sinkholes, grikes, solutional openings, etc. (>10 features/ha).
Subsurface Karst Potential
L – Low Potential Normal drainage patterns, low hydraulic head, low relief. Subsurface openings not anticipated.
M – Moderate Potential No known caves or cave entrances, but with adequate hydraulic head and site conditions suitable for subsurface opening development (e.g., bench with sinking streams on upslope karst unit boundary).
H – High Potential Known caves/cave entrances, sinking streams, springs, and high hydraulic gradient.

The first type of information to be collected is bedrock unit name, type and anticipated proportion of soluble bedrock (see Tables 3.1 and 3.2). The anticipated proportion of soluble bedrock can be used where the geological boundary of a karst unit is unclear (e.g., buried by surficial cover), or if the unit is comprised of pods/interbeds of soluble bedrock. In addition, a heading is included in Table 3.1 for a Yes or No response as to whether soluble bedrock was encountered within a polygon.

The symbols, terms and codes for surficial material type and texture can be applied as they are for terrain mapping (see Howes and Kenk, 1998); likewise for geological processes and associated sub-classes. Similarly, terrain drainage codes and slope classes can be used as described in *Guidelines and Standards for Terrain Mapping in British Columbia* (RIC, 1996). Two refinements are suggested for the surficial material thickness codes. The first is the addition of a shallow veneer code, (s) 20–50 cm for surficial material thickness, and the second is the addition of outcrop descriptors to each of the thickness codes (see Table 3.2). Another refinement is to ensure more common usage of the organic material code (O) for the forest litter overlying karst surfaces (see Table 3.2). Typically, in many coastal forested areas, this is the only material present on karst surfaces, and can be easily lost into vertical solutional openings in the epikarst during forestry activities. The identification of this material, its texture (e.g., fibric or misic) and thickness, at any depth, is therefore an important part of the data collection procedure.

Surface expression codes as outlined in the *Terrain Classification System for British Columbia* (RIC, 1997) can be used for karst mapping, but are somewhat limited in their ability to describe the karst landscape. A series of mapping codes for karst micro-topography[11] were developed based on the karst inventory field trials (see Table 3.3). The micro-topography codes can be used to classify the general karst surface that is within the field of vision in forested terrain (e.g., 10–100 m). These codes can also be used for rating karst vulnerability potential, and can assist in forest development planning (e.g., by ensuring roads are located away from identified areas of closely spaced hums and hollows).

Table 3.3. Suggested mapping codes for karst micro-topography

kc	– closely spaced karst hums and hollows (<50 m between hum centre points and typically >10 m in elevation between top of hums and base of depressions)
kh	– moderately spaced hums and hollows (>50 m and <100 m between hum centre points, and typically 5–10 m elevation difference between top of hums and base of depressions)
kw	– widely spaced hums and hollows (>100 m between hum centre points and <5 m elevation difference between top of hums and base of depressions)
kb	– karst bench and bluff complex (narrow linear bluffs and benches <50 m wide and too small to map as individual polygon)
ki	– irregular karst surface with numerous depressions (e.g., sinkholes)
km	– moderately irregular karst surface with occasional depressions (e.g., sinkholes)
ks	– slightly irregular karst surface with rare depressions (e.g., sinkholes)

Note: These codes have not been field tested, but were developed based on findings from karst inventory field trials. Further additions to these codes could be made to reflect local site conditions.

[11] Micro-topography, for the purpose of this procedure, is defined as small scale topography within the field of vision in forested karst. Typically, this is in the order of >1–5 m change in elevation and >10–50 m in horizontal distance.

Categories for the principal karst-mapping attributes of epikarst development, surface karst feature density, and subsurface karst potential are outlined in Table 3.2. These categories were developed during the karst inventory field trials, and are intended to cover most of the karst characteristics encountered in forested areas of coastal and interior British Columbia. However, some minor refinements to these categories may be required to adjust to local conditions.

Determination of epikarst development is based on a visual estimation of the depth and frequency of vertical solutional openings. This can be done by referring to the descriptions for each of the epikarst development categories in Table 3.2, or by using a visual chart for determining epikarst development at the KFA level (refer to Figure 4.5, page 40).

Surface karst feature density is determined by estimating the number of surface karst features per ha (by considering a 100 m by 100 m square, or a circle with a radius of approximately 56.4 m). For the purpose of this procedure, surface karst features can include solutional openings (e.g., grikes), sinkholes, shafts and cave entrances. These features must have one measurable surface dimension (length, width, diameter) greater than 2 m, but must be less than 20 m in size. Typically, any features greater than 20 m in size should be plotted as an on-site symbol, and likely represent a 'significant' feature (see Section 3.3.3). Estimation of surface karst feature density can be done using the descriptive categories provided in Table 3.2, or by using the visual chart for determining surface karst feature density at the KFA level (refer to Figure 4.9, p. 47).

No subsurface evaluation, other than possibly a brief cave entrance examination, is anticipated during the planning-level inventory. Care should be taken to closely locate and geo-reference cave entrances and other openings to assist further inventories at the KFA level. The categories for subsurface karst potential (low, moderate and high; see Table 3.2) are based on a combination of direct field observations and a general understanding of the likely karst processes at a site.

Procedure for Vulnerability Potential Rating

The final stage of karst mapping at the planning level is the allocation of vulnerability potential ratings to karst polygons. This procedure is a qualitative evaluation of the karst and terrain characteristics of each polygon, and is based on some general guidelines (outlined below and in Table 3.4), but primarily relies upon the experience and judgement of the mapper completing the work. This approach is similar in concept to that used for deriving stability classes from 1:20 000 scale terrain mapping, and allows the mapper a certain level of professional flexibility. Four rating categories of vulnerability potential are used—low (L), moderate (M), high (H) and very high (V)—coinciding with the four vulnerability assessment categories used at the KFA level. (The differences between vulnerability potential ratings at the planning level and vulnerability assessments at the KFA level are highlighted in Section 1.1).

The process for determining vulnerability potential ratings is qualitative, and considers karst attributes in their relative order of importance—primary, secondary and tertiary (see Table 3.4). Epikarst development, surface karst feature density and subsurface karst potential are considered the primary attributes for determining vulnerability potential ratings. Secondary attributes that should be considered include surficial material type and thickness, bedrock type and proportion, and karst micro-topography. Tertiary attributes include slope class, drainage class, geomorphic processes and other surface expressions.

Table 3.4. Determination of planning-level vulnerability potential rating and order of attribute importance

Primary Attributes	– epikarst development
	– surface karst feature density
	– subsurface karst potential
Secondary Attributes	– surficial material type and thickness
	– bedrock type and proportion
	– karst micro-topography
Tertiary Attributes	– slope class
	– drainage class
	– geomorphic processes
	– other surface expressions

In general, the highest rating category for a karst attribute (see Table 3.2) should be used to derive the overall vulnerability potential rating. For example, a karst polygon with slightly developed epikarst, a low density of karst features and a high subsurface karst potential should receive a high vulnerability potential rating.

It is recommended that mappers develop a set of tabular criteria that are site-specific descriptions for each vulnerability potential rating (low, moderate, high and very high). Examples of vulnerability potential ratings for typical karst terrain conditions in British Columbia are provided in Table 3.5.

The presence of unique or unusual flora/fauna or associated habitats can also influence the vulnerability potential ratings for some polygons. This is discussed further in Section 3.3.5.

In general, the unpredictable nature of karst formation processes requires considerable ground coverage of the karst polygons until the conditions are well characterized. The approach of the vulnerability potential mapping procedure is constrained, in part, by the anticipated end use, as this can influence the amount of detail and field checking required (see Table 3.6).

If the main focus of the mapping is to direct a KFA, field checking should focus on identifying the boundaries between low vulnerability potential polygons and the other categories of moderate, high and very high, as all of the latter will require a KFA. Clumping of the moderate and high polygons in this case would be acceptable. Terrain survey intensity levels (TSILs) with 20–50% polygon coverage (TSIL C) or less, would likely cover the ground effectively in this situation.

If an additional purpose of the mapping is to assist forest development planning in the design of cutblocks and road layout, identification of the boundaries of very high vulnerability potential polygons would be important, as these areas are unlikely to be suitable for forestry activities. In this case, the mapping would require more field checking, with approximately 50–75% polygon coverage (TSIL B).

If another requirement of the mapping is to determine the amount of future ground searching for a KFA, it may be necessary to accurately differentiate the moderate and high vulnerability potential polygons. This would likely require 75–100% polygon coverage (TSIL A).

Table 3.5. Examples of planning-level vulnerability potential ratings in forested karst terrain in British Columbia

Vulnerability potential rating	Description of karst terrain conditions*
Low	Low vulnerability potential karst polygons could include a range of terrain conditions that vary from moderately steep sloping karst surfaces with thin soil cover, little epikarst development and no karst features, to a gentle to moderate sloping bench with a thick till blanket, moderately well-developed epikarst and isolated surface karst features. A coastal BC example of low vulnerability terrain could be a valley bottom with a very thick glacial till cover and evidence of epikarst development only exposed in road cuts, with no surface karst features apparent. An interior BC example could include an exposed limestone or dolomite ridge, with a thin soil cover, and little to no epikarst development or surface karst features.
Moderate	Moderate karst vulnerability potential polygons could include a relatively wide range of terrain conditions. Such terrain conditions could include moderately to well-developed epikarst, with a thin soil veneer (<50 cm) and a low number (1–5/ha) of surface karst features. Alternatively, terrain conditions could include a blanket of soil, with slight to no epikarst development and a moderate number (5–10/ha) of surface karst features. In most cases, it would be anticipated that a moderate or possibly high potential for subsurface openings exists. An interior BC example of this type of terrain would be a gentle to moderate sloping bench, with a blanket of till cover and little to no epikarst development, but with a significant number of sinkholes, swallets and springs.
High	High karst vulnerability potential polygons could include terrain with moderate to well-developed (1–2 m deep) epikarst, a high density (10–20/ha) of surface karst features and a high likelihood for subsurface karst openings. An example of this type of terrain on coastal BC could include a gentle sloping bench, with a thin till veneer exposing a distinct solutional epikarst surface that is interspersed with a number of surface karst features, including cave entrances. A series of sinking streams and swallets could also be present on the upper contact of the bench, confirming the presence of subsurface openings.
Very High	Karst polygons with very high vulnerability potential ratings can be anticipated to include terrain with a combination of well-developed epikarst (>1–2 m depth), numerous (>20/ha) mesoscale surface karst features and known subsurface openings or caves. In this case, there would be a high level of connectivity between the surface and subsurface. An example of this type of terrain on coastal BC might include a moderate sloping bench, with a trace of forest floor cover over a very irregular surface, exposing extensive areas of deep solutional epikarst, interspersed by numerous single and coalescing surface karst features (e.g., sinkholes, grikes and cave entrances). The cave entrances could lead into a subsurface system that has significant decorations and/or contains important habitat for cave fauna.

* This table provides descriptions and examples for various karst vulnerability potential ratings, and is based on experience within forested karst areas of BC. It is not anticipated that the descriptions will cover all possible examples; however, they will provide some indication of the typical terrain and karst conditions that might be encountered.

Table 3.6. Karst vulnerability potential ratings at the planning level and their likely uses and applications

Karst vulnerability potential ratings at the planning level	Uses and applications			
	1 Directing KFA needs	2 Strategic planning	3 Forest development planning (e.g., design of cutblock and road layout)	4 Anticipated KFA ground searching and cave inspections
Low	No KFA required	Development can likely proceed, but with some restrictions	Little modification to standard forest practices	Cursory ground search
Moderate	KFA required		Some to considerable modification to standard forest practices	Less intense ground search and possible cave inspections
High				Intense surface ground search and probable cave inspections
Very High		Development likely to be restricted	Highly specialized practices likely required	Highly detailed ground search and cave inspections

Example A. If the main applications of vulnerability potential mapping are 1 and 2, the field work should focus on identifying polygons with low and very high ratings. Polygons with moderate and high ratings require less separation and can be grouped together if required.

Example B. If the main applications of the vulnerability potential mapping are 1, 3 and 4, the field work should aim to separate all four ratings.

3.3.3 Task 3 – Identification of Significant Surface Karst Features and Hydrological Features

The identification of significant surface karst features at the planning level is important as they provide a general sense of the magnitude of the karst system within a specific area. This information is useful for both assisting forest development planning (e.g., layout of cutblocks or roads) and for directing further inventory work. At this level, the term 'significant' for a surface karst feature is somewhat subjective, and is generally a function of size. However, a group of small features (e.g., swallets or springs) could also be significant, as would a small cave entrance that leads into a large cave system. (Evaluating the significance of surface karst features is further discussed in Section 4.4.3 and in Appendix C.) Many large surface karst features, typically greater than 20 m in surface dimensions (width, length, diameter), can be identified in air photos by canopy gaps in the forest cover (e.g., a karst canyon or large sinkhole). Field work carried out during the planning-level inventory should be designed to intersect as many of these significant features as possible.

Another important consideration is to identify potential areas where significant karst features might be present, but are not visible in the air photos. This can be done by using predictive techniques based on an understanding of karst-forming processes. For example, a gully extending up a slope underlain by limestone might lead to a karst spring, or the upper geological boundary of a karst unit would be a likely site for swallets.

Details on measuring and classifying surface karst features are outlined in Section 4.4.3 and Appendix D. A list of on-site map symbols used to indicate types of surface karst features is included in Figure 4.7 (p. 44).

Streams on karst terrain can be identified, mapped and classified at the planning level, as outlined in Figure 4.7. However, the main emphasis should be on mapping the characteristics of larger streams, or ones that display distinctive karst processes (e.g., losing, sinking or gaining streams). Streams are not directly included in the vulnerability potential rating because of the inherent complexity of integrating linear features with polygons. However, in many cases, there is a direct correlation between the number of streams and surface karst features. For example, a large number of streams flowing onto an upper karst boundary will likely develop a large number of swallets.

3.3.4 Task 4 – Determination of Karst Catchment and Hydrology

One characteristic of karst terrain that differs significantly from non-karst terrain is its hydrological system. Typically, karst hydrological systems can include complex subsurface drainage networks and catchment areas that do not necessarily follow topographic divides, and, in many cases, cross them. Hence, karst hydrological systems can be characterized as highly variable and difficult to predict from surface features. Data from Tasks 1, 2 and 3 can be useful in determining the extent of the karst catchment for a site and the likely subsurface hydrology. In some cases, subsurface hydrological flow paths can be inferred from the surface drainage patterns, site geology and surface karst features; however, in most cases, the subsurface hydrological flow paths are less clear. At the planning level, it is possible to delineate watershed divides and determine the karst and non-karst components of the topographic catchment. The adjacent non-karst component of the topographic catchment, if upslope from the karst unit, can have a significant influence on the karst hydrology down-slope. Where the karst unit extends across the watershed divide, there exists some possibility for adjoining karst and non-karst catchments (see Section 3.2 and Figure 3.2). A valuable tool for evaluating the extent of karst catchments and subsurface flow paths is dye tracing.

Dye Tracing

Dye tracing is a well-accepted methodology for evaluating karst hydrological systems in forested terrain (Stokes and Griffiths, 2000). It is undertaken using one or more flourescent dyes that are injected into a recharge site (e.g., sinking stream), and then tracked through sampler sites located at likely discharge locations (e.g., springs). Typical objectives for a planning-level dye tracing investigation might include determining:

- the likely extent of the catchment area;
- the main recharge and discharge areas;
- the location and connectivity of subsurface conduits (or groundwater flow paths); and
- the subsurface flow response/transit times.

Dye tracing conducted at the planning level is not intended to be an exhaustive procedure, but rather to provide a general idea of the karst hydrology, and give an indication as to whether further detailed investigation may, or may not, be required.

Dye tracing projects should be designed and carried out by experienced personnel. Conceptual design should be completed prior to any field work, where clear objectives and favourable locations for dye injection and sampler sites are identified. Appropriate dyes and samplers should be chosen for the site conditions. Various interested agencies (e.g., Federal Department of Fisheries and Oceans, and BC Environment) should be informed of the

location and timing of the dye tracing. Prior to dye placement, water samples should be taken at injection and collection sites for background analysis, particularly if previous dye tracing has been carried out in the area. Water at the injection and collection sites should be tested for temperature, pH, dissolved oxygen and conductivity. Water flow estimates should be made at both injection and sampler sites. Precipitation data should be obtained from a nearby registered rain gauge if available; if not available, a simple rain gauge should be set up at a suitable location for the duration of the field work.

Retrieval and replacement of dye samplers should be carried out strictly, according to approved procedures. A labeling protocol and chain of custody should be implemented, with all samples being shipped directly to an approved laboratory for analysis. These samples should be prepared and analyzed according to accepted laboratory standards and procedures. Analytical results should be certified by the laboratory. Following completion of the dye tracing and analysis, a map (or layer in a GIS data base) should be completed showing dye paths and travel times of groundwater flow, boundaries of the recharge areas, insurgences and exsurgences. For further explanation and examples of dye tracing techniques, materials and analytical procedures, refer to Stokes and Griffiths (2000).

The need for dye tracing is highly dependent on site conditions, and relies on the following factors:

1. the anticipated complexity of the groundwater flow paths;
2. the number and size of discrete inflow and outflow sites; and
3. the complexity and size of the karst catchments.

Table 3.7 provides some general guidelines for determining the need for dye tracing. The intent of the table is not to cover all situations, but rather to provide an indication of some of the site conditions where dye tracing could be utilized.

3.3.5 Task 5 – Identification of Karst Flora and Fauna, and Associated Habitats

The identification and evaluation of unique or unusual karst flora and fauna, and their associated habitats, is a complex and specialized field (e.g., Chapman, 1993) with only a few specialists worldwide capable of completing full karst biota inventories either on the surface or subsurface. Nevertheless, a pragmatic approach to identifying karst flora and fauna, and their associated habitats, is recommended for both planning-level inventories and KFAs (see Section 4.4.7). The recommended approach is to focus on likely habitats for karst biota (see Table 3.8), rather than trying to identify any particular fauna or flora species. Some of the key habitats for karst biota occur around karst springs; cave entrances; well-developed epikarst; solutional grike fields; along karst bluffs or canyons; and around large and/or deep sinkholes, swallets and cave entrances. All of these habitats are where a variety of karst flora and fauna species can exist under relatively shaded and consistent temperature conditions. Any sites where there is a diversity of plant species is also likely to be good habitat for karst fauna.

Identified karst habitats should be carefully described and mapped as part of the planning-level inventory. If karst flora/fauna habitat sites are considered significantly large or unusual, they could be utilized to influence the vulnerability potential rating of a polygon by increasing it by one or possibly two levels (e.g., from low to moderate, or low to high). This would ensure further evaluation of these sites at the KFA level. In cases where habitat sites are small or point features, it is suggested they be highlighted as specific locations for further inventory work, rather than be used to influence the overall polygon vulnerability potential rating.

Table 3.7. Determining likely dye tracing requirements at the planning level

	Karst Type		
	Young or Merokarst (Karst development follows existing surface drainage) ----------→		**Old or Holokarst** (Karst with little to no surface runoff or streams)
	Subsurface hydrology		
Catchment conditions	Relatively straight forward subsurface hydrology anticipated	Moderately complex subsurface hydrology anticipated	Complex subsurface hydrology anticipated
Karst unit confined to one topographic catchment, with small upslope non-karst component	M	S	D
Karst unit limited in extent, but crosses at least one topographic watershed/major creek drainage, with considerable upslope non-karst component	M	S	D
Karst unit crosses a number of topographic watershed divides, and has adjoining karst and non-karst catchments.	S	D	D

M – Most of the subsurface hydrological links at the site can be determined from the surface drainage patterns and hydrological features. Dye tracing is unlikely to uncover subsurface flow paths different from the ones determined from the surface drainage patterns.

S – Some of the subsurface hydrological links can be inferred from the location of hydrological features. However, there is some element of doubt. Dye tracing is suggested to confirm the postulated subsurface flow paths and the likely extent of the catchment.

D – Determination of the subsurface flow paths from the surface drainage patterns and hydrological features alone could be misleading. Dye tracing is highly recommended to confirm the subsurface flow paths and the likely extent of the catchment areas.

Table 3.8. Preliminary list of habitats for karst-specific flora and fauna

Karst habitat	Mosses	Lichens	Plants	Insects	Mammals	Amphibians/ Fish
Cliff/bluff	L	L	L	L	U	P
Canyon	L	L	L	L	P	L
Large sinkhole	P	P	L	P	U	U
Swallet	P	P	L	L	P	L
Spring	L	P	L	L	L	L
Large grike	L	L	L	P	U	U
Well-developed epikarst	L	L	L	P	U	U
Cave entrance	L	P	L	L	L	P
Subsurface terrestrial	V	V	V	L	P	P
Subsurface aquatic	V	V	V	L	U	L

L – likely to be encountered
P – possibly encountered
U – unlikely to be encountered
V – very unlikely to be encountered

3.3.6 Task 6 – Identification of Geomorphic Hazards

The identification of geomorphic hazards that could potentially impact a karst unit is another planning-level inventory task. These hazards can occur on the karst unit itself or upslope of the karst unit, and are the result of natural disturbances or man-made activities, including those related to mass wasting, soil erosion and sediment transport, windthrow, and burned areas (see Appendix B). At the planning level, the extent of this task is to record the location, type and extent of the geomorphic hazards, and briefly evaluate their possible consequences. The hazards are highlighted on the final map, and described in the accompanying report so that further evaluation can be carried out during a KFA, if required.

3.4 Suggested Standards for Reports, Map Presentation and Personnel

A written report covering all tasks completed should accompany the maps compiled for each project. The report should cover project objectives, information used, regional geomorphology, bedrock geology, karst hydrology, office and field methodologies, and a discussion of results, conclusions and recommendations. The karst mapping report should approximately follow the guidelines in Section 11 of *Guidelines and Standards for Terrain Mapping in British Columbia* (RIC, 1996). The report should also contain information with respect to data reliability, karst polygon coverage, dye tracing conducted and any limitations (e.g., areas not assessed).

Bedrock mapping symbols, maps and cross-sections should be completed to standards outlined in Section 3 of *Specifications and Guidelines for Bedrock Mapping in British Columbia* (RIC, 1996). Karst vulnerability potential maps should closely follow the standards of Sections 8 and 9 in *Guidelines and Standards for Terrain Mapping in British Columbia* (RIC, 1996). The karst mapping can be integrated into a GIS system using separate layers for topography, streams, karst unit boundaries, bedrock information, surface karst features, karst

polygons, karst catchment and subsurface flow paths. Data utilized for the karst polygons should be provided as a digital data base and included on the map legend. Manual compilation of maps and data is acceptable, providing the appropriate standards are achieved.

It is recommended that planning-level inventories be carried out by a professional with experience in bedrock geology, terrain mapping, and karst geomorphological and hydrological processes. In addition, it is suggested that the person accompanying the professional in the field be a technician who is familiar with karst features and cave entrance inspection procedures. The technician would be able to locate and mark any surface karst features encountered, and rove off the main traverse route to examine any areas of interest. In some cases, rapid examination and inspection of cave entrances could be made during the course of the field work. Continual radio communication between the two workers is essential. Any dye tracing would require the input of an experienced karst hydrologist for project design and data analysis.

3.5 Linkages to the KFA and the Reconnaissance-level Inventory

One of the primary goals of the detailed planning-level inventory and vulnerability potential rating scheme is to identify karst polygons that require further karst inventory and vulnerability assessment at the KFA level. The methodology for the planning-level vulnerability potential rating procedure is intentionally conservative, defaulting, in most cases, to the highest rating category of the controlling attribute (see Section 3.3.2). This ensures that any karst polygons of concern are identified and evaluated in more detail at the KFA level. In general, polygons with low vulnerability potential ratings would not normally require a KFA, whereas those polygons with a moderate, high or very high rating would receive a KFA.

Findings and data from the planning-level inventory should be linked back to the reconnaissance-level inventory to refine karst potential ratings for Criteria #1 and #2, and to add further known cave and karst inventory information (Criterion #3). These data can then be extrapolated to adjacent areas where little or no known karst information is available.

4.0 Karst Field Assessment

4.1 Goals, Objectives and Approach

This section describes the methodology used for completing a karst field assessment (KFA). The primary goals of the KFA are to obtain detailed information on the karst system and resources adjacent to and within an area of proposed development, and to assess the vulnerability of the karst unit (see Section 4.6). For example, a KFA would typically be carried out in support of an application for forest development at the cutblock level, and would be included in a silvicultural prescription. This information could then be used to prescribe suitable forest practices for specific activities, as outlined in the *Karst Management Handbook for British Columbia*.

The principal objectives of the KFA are to:

- determine the boundaries and likely three-dimensional nature of the karst unit of interest;
- evaluate the contributing karst and non-karst components of the karst catchment;
- locate, identify and classify key surface karst features and attributes;
- evaluate the significance of surface karst features;
- define karst polygon boundaries;
- evaluate and map subsurface karst to the level and extent required;
- derive vulnerability ratings for each karst polygon;
- determine the need for further investigation of subsurface hydrology (i.e., dye tracing);
- identify the need for further specialized inventories (e.g., archaeological, paleontological, karst flora/fauna); and
- identify any geomorphic hazards that could potentially impact the karst unit.

At the KFA level, greater importance is placed on detailed measurement, classification and evaluation of the attributes of a relatively small karst area of interest (e.g., proposed cutblock), as compared to the planning level where the aim is to obtain a general sense of the types and distribution of karst attributes that cover a larger area (e.g., watershed).

Initiation of a KFA should occur under the following circumstances:

- proposed development is underlain by carbonate bedrock;
- development is proposed on non-carbonate lands located within the contributing drainage basin of known or suspected carbonate units;[12]
- reconnaissance-level karst potential maps indicate that the area proposed for development may be underlain by karst;
- a planning-level inventory identifies karst polygons with moderate, high or very high vulnerability potential ratings in or around an area of proposed development;
- there is previous knowledge of karst in or around an area of proposed development; or
- karst features are identified in or around an area of proposed development.

While a KFA primarily focuses on a surface karst inventory, subsurface examination and mapping is required where caves occur, so as to effectively evaluate the three-dimensional aspects of the karst system and provide specific information that may be required for

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[12] In this case, the KFA would be carried out on the known or suspected karst units located downstream of the proposed development, including any contiguous karst units in adjacent or adjoining drainage basins.

applying effective management prescriptions (e.g., location of caves with thin ceilings, or identification of infiltration zones over significant caves).

Overall, the KFA focuses on identifying karst attributes that are relatively stable and reliably mapped. The key attributes that should be located, identified and measured during a KFA are provided in Appendix B.

In terms of inventory scheduling and organization, a KFA, in many cases, is likely to be the first karst inventory work completed for an area, other than the reconnaissance (1:250 000) karst potential maps. In this case, consideration should be given to using or adapting some of the broader-based tasks outlined at the planning level (see Tasks 1, 3 and 4 of Section 3.3) to get a general sense of the karst, not only within the area of interest, but also in the surrounding region (see Sections 4.2 and 4.3).

Typically, the polygon data and boundaries provided by reconnaissance-level karst potential mapping cannot be directly used at the KFA level because of the large differences in scale. However, the reconnaissance-level mapping, combined with some field checking, can be used to give an overall picture as to the possible size and complexity of a karst system. If available, planning-level karst polygons can be used as preliminary polygons at the KFA level.

4.2 Office Review

There are several stages to successfully completing a KFA, beginning with an office review, followed by field activities, and report/map compilation (see Figure 4.1). An office review prior to initiation of field activities is critical to ensure that the objectives and goals of the KFA are well defined and understood. A considerable amount of valuable information can be gained by collecting and analyzing existing data. This helps ensure that field activities are well directed and efficient, and avoids possible duplication.

The following tasks should be completed during the office review stage of a KFA:

- Review data from pre-existing reconnaissance-level and planning-level karst inventories (if available), including any dye tracing results. Obtain any other karst inventory or cave information for both the area of interest and adjacent areas.
- Obtain basic information on the karst unit from available air photos, and topography, bedrock geology, surficial geology and terrain maps.
- Determine any relevant requirements or protocols from FPC guidelines, higher level plans, or cave/karst management plans. Review the types of proposed development activities (e.g., road locations, harvesting methods). Obtain any local knowledge on the area or adjacent areas (e.g., windthrow potential).
- Identify and gather any other existing information on terrain features, soils, topography, ecosystems and flora/fauna of the karst unit using available mapping and other inventories (e.g., terrestrial ecosystem, terrain mapping, fish habitat, forest cover).
- Construct a base map at the required scale either manually or in digital format using a GIS system with a series of layers. Layers should be developed for contours, bedrock geology, surface streams, vegetation, soils (thickness/type) and proposed development areas.
- Plot any known surface karst features on the base map using points, lines and approved symbol conventions. Project the outline of any known cave passage in plan view. Plot any known insurgences or exsurgences (e.g., swallets or springs, respectively).
- Delineate the catchment area for the karst unit of interest and set preliminary limits for the KFA.

OFFICE REVIEW:

Obtain all previous karst information – reconnaissance-level karst potential maps, planning-level karst inventories, other karst inventory or cave information for the area of interest and/or adjacent areas.

Gather all other available information – air photos; detailed topography, bedrock geology, surficial geology and terrain maps; data on soils, vegetation/ecosystems, forest cover and fish habitat.

Construct a base map either manually or in digital format with a series of layers – include layers for contours, bedrock geology, karst unit boundaries, the karst catchment area, streams, vegetation, soils (thickness/type) and proposed development.

Plot all karst data on the base map using standard symbol conventions – include surface karst features, epikarst zones, streams, hydrological features and the outline of any known cave passages in plan view.

Determine preliminary boundaries for karst polygons – use changes in topography, stream patterns, air photo information, bedrock geology maps, any previously known karst data or data from planning-level karst polygons, if available.

FIELD WORK ACTIVITIES:

Preliminary Field Review to determine:

- likely boundaries of the karst unit and karst catchment area;
- the presence of any significant (large) surface karst features or zones; and
- surface karst characteristics in adjacent logged areas or open canopy areas.

Ground Searching and Surface Mapping to evaluate:

- the karst unit boundaries;
- soil thickness and texture;
- any karst-specific flora and fauna.
- surface epikarst development;
- surface karst features; and

Stream Evaluation to determine:

- the spatial location and reach breaks of streams;
- stream characteristics (e.g., sinking, losing, gaining, rising);
- the location of points where streams lose water to the subsurface; and
- the significance of karst features receiving the water (recipient features).

Subsurface Inspection and Mapping to:

- assess caves for their significance;
- collect survey data to establish the location of the cave system with respect to the surface; and
- help determine the subsurface karst potential for the area.

REPORT AND MAP COMPILATION:

The KFA report should include:

- objectives, scope, limitations and location of project;
- description of field methodologies;
- results of the vulnerability assessment process, addressing any limitations or concerns;
- discussion of the potential effects of proposed development within the karst area of interest; and
- conclusions and recommendations for management prescriptions or mitigative measures.

Attachments or appendices to the KFA report should include:

- a regional location map (1:20 000 scale or greater);
- a 1:5000 or 1:10 000 scale map that includes karst unit boundaries, karst catchment area, epikarst development, surface karst feature density, subsurface karst potential and rated vulnerability polygons;
- three-dimensional schematics or drawings of the karst system in perspective view; and
- references, glossary and representative photographs.

Figure 4.1. Methodology for the karst field assessment.

- Determine preliminary boundaries for karst polygons using changes in topography, stream patterns, air photo interpretation or any known karst information. If available, use data from planning-level karst polygons to develop preliminary polygon boundaries.
- Develop a comprehensive plan for carrying out field activities both in terms of logistics and appropriate inventory techniques (e.g., types of ground searching methods).

4.2.1 Determining Preliminary Limits for a KFA

Part of the office review is to determine the preliminary limits of the area to be covered by a KFA. This is typically the area of proposed development and/or the area potentially affected by the development. In general, KFAs will focus on a small area of karst that occurs within a larger karst system or unit, but they can also focus on a portion of a karst unit located downstream of a proposed development located within the karst catchment. The limits of a KFA can be greater or smaller than the area of proposed development, depending on the boundaries of the karst unit, the extent of the karst catchment and the known extent of any subsurface openings or cave systems.

If the boundaries between the karst and non-karst terrain have been defined within a proposed development area, it is generally not necessary to carry the KFA procedures onto the non-karst portion of the area, except for the evaluation of streams (see Section 4.4.5) and the investigation of geomorphic hazards (see Section 4.4.8). This can help minimize the surface limits of a KFA, as well as the time and effort required to complete the procedure.

Typically, a karst catchment area includes both the karst hydrological system itself and any upland contributing non-karst catchments. If the karst unit extends, or is contiguous across a topographic divide, it is possible that subsurface water flow from other karst and upland non-karst units in different drainage basins can contribute subsurface water to the karst area of interest. The limits of a KFA cannot, in a practical sense, include all of the karst catchment, as in many cases this is both unknown and potentially large in size. In some cases, it may be necessary to determine arbitrary limits to a KFA based on a 'best estimate' of the karst catchment.

Dye tracing can be a valuable tool for assessing subsurface hydrology and the extent of karst catchments. In some instances, dye tracing results may be available (e.g., from a planning-level inventory or other source) to assist with catchment area determination and subsurface hydrology; however, as a general rule, the availability of existing dye tracing information is likely to be minimal. For details on conducting dye tracing, see Section 3.3.4.

Where caves or other subsurface openings are known to underlie and extend beyond the boundaries of the proposed development area, it may be necessary to increase the limits of the KFA. For example, a cave system could be encountered beneath a cutblock or road location that might continue into adjacent areas where it could still be impacted by activities carried out within the cutblock.

4.3 Field Activities

The field portion of a KFA requires the gathering of karst attribute data on the surface, and to a lesser extent, from the subsurface (see Figure 4.2). Elements of the karst attribute data can range from points (e.g., certain surface karst features), lines (e.g., karst unit boundaries), to polygons with similar characteristics (e.g., epikarst zones). In order to collect information on these various attributes, a number of different field activities are required to ensure a thorough evaluation of the karst unit/area of interest. These field activities can be sub-divided as follows:

- preliminary field review of the karst unit and nearby areas;
- ground searching and mapping of karst attributes;
- stream evaluation; and
- subsurface investigation and mapping.

Some overlap or concurrency is likely to occur between the various activities (e.g., an evaluation of streams may be carried out during ground searching).

Field activities are applied with varying emphasis, with most of the field time generally directed towards ground searching and mapping. However, if a significant number of streams or caves are present, more time might be spent on the evaluation of those features. The approach to the inventory work would be slightly different if only a road location needed to be assessed, as roads are linear features. In the case of road construction, the major impacts on the karst system are related to surface and subsurface hydrology, and the integrity of surface and subsurface features. To inventory road locations, detailed ground searching and mapping is carried out in the immediate area of the road centre line (e.g., approximately 50 m either side), while less detailed searching and mapping is completed for the surrounding area, depending on the level of previous knowledge around the site. Stream evaluations are particularly important for road crossing sites.

4.3.1 Preliminary Field Review

Prior to initiation of detailed field work, a preliminary field visit to the karst unit of interest is advised, particularly if little to no previous information or knowledge of the area is available. This is used to confirm some of the general findings of the office-based work, and to provide some idea of how the karst unit of interest fits within the surrounding karst area or system. The preliminary field review can be carried out in a number of ways—aerial (e.g., helicopter), vehicle or on foot—and is similar to a regional planning-level inventory in that it would aim to determine:

- the likely boundaries of the karst unit;
- the likely boundaries of the catchment area (karst and non-karst);
- the presence of any significant surface karst features or zones; and
- surface karst characteristics in adjacent logged areas or open canopy areas (e.g., subalpine).

Findings from the preliminary field review may influence the anticipated approach or focus for the other more detailed field activities associated with a KFA. In cases where the area is known, or experience from similar or adjacent areas is available, preliminary field reviews may not be required.

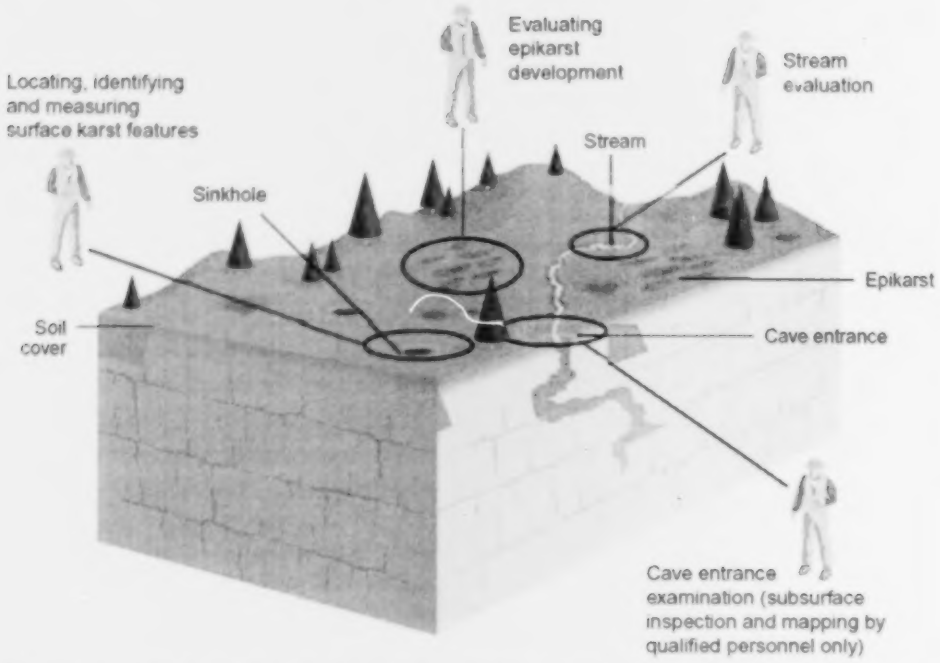


Figure 4.2. Field activities for collecting key karst attribute data.

4.3.2 Ground Searching and Surface Mapping

Ground searching and surface mapping are required to locate, identify, measure and evaluate a number of karst attributes for a KFA. The key attributes can be broadly divided as follows:

- the karst unit boundaries (Section 4.4.1);
- epikarst (Section 4.4.2);
- soil thickness and texture (Section 4.4.2);
- surface karst features (4.4.3);
- karst roughness (Section 4.4.4);
- streams (Section 4.4.5);
- subsurface karst potential (Section 4.4.6); and
- karst flora and fauna (Section 4.4.7).

Geomorphic hazards that could potentially impact the karst unit should be located, identified and briefly examined during a KFA (see Section 4.4.8).

The primary aim of ground searching is to locate and identify discrete surface karst features or point data (e.g., cave entrances), whereas surface mapping is required to identify linear karst features or zones of similar surface karst features. Ground searching and surface mapping can be completed at the same time and should complement each other where possible. The end product of this field activity should include a set of field notes or completed field forms, as well as an annotated field map showing the distribution of karst attributes.

Ground searching can be carried out using a number of techniques that have been successfully utilized for karst inventory work in British Columbia. These techniques are

described in *Searching for Cave Entrances in Old-growth Forests: An Overview of Ground-Based Methods Employed in North and Central Vancouver Island, British Columbia* (Griffiths, 1997). (See Appendix E.)

The four most common ground searching techniques, in order of increasing search intensity, are:

- reconnaissance or linear transect search;
- judgemental search;
- multiple transect or grid search; and
- total (saturation) search.

See Figure 4.3 for a graphic depiction of the four ground searching techniques.

The main intent of ground searching is to confirm the boundaries of the karst unit, locate surface karst features, and evaluate other karst attributes such as soil type/thickness and epikarst development. The four different ground searching techniques can be combined, stratified or modified to suit local field conditions. Determination of the best type of ground searching technique to use is based on the experience of the user and the type of terrain encountered.

The reconnaissance or linear transect search can be used as an initial field orientation, and consists of a traverse line or bearing with minor deviations across the inventory area. This type of search is also suitable for road locations or streams that cross karst, where a linear route is followed.

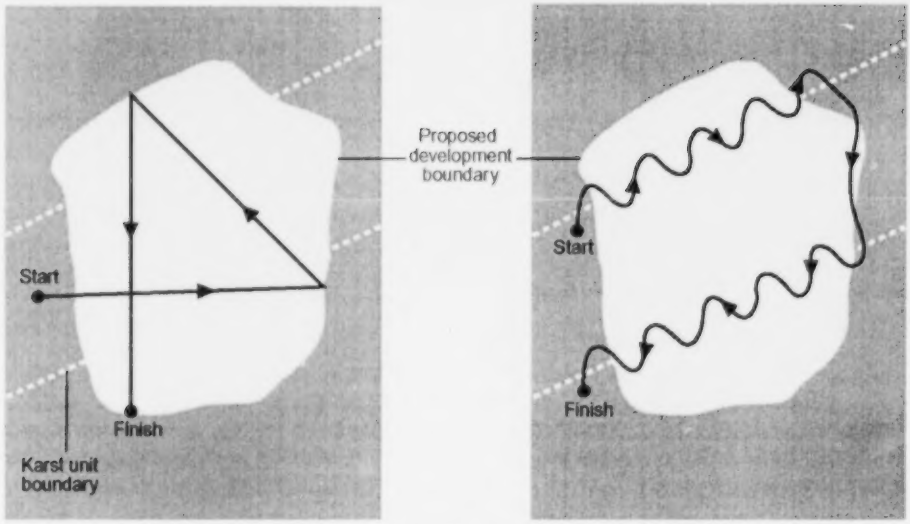
The judgemental search is based on the recognition that karst development generally does not occur in a random fashion, and that it is possible to identify associations between karst development and terrain variables (e.g., the correlation between swallets and upper limestone contacts). By using this approach, an experienced field worker can predict where features are more likely to be found, and traverse routes can be designed and optimized accordingly. This can be an effective method for concentrating field work on critical areas and avoiding detailed work in areas of less concern.

The multiple transect or grid search is useful where discrete karst features (e.g., cave entrances) are less predictable and spread more randomly throughout an area. The grid layout, spacing and orientation of search lines is based on practical considerations (e.g., understorey thickness, terrain steepness) and an assessment of where the most information might be obtained. Typically, these grids can be constructed by a single compass person along a centre line, with lateral rovers identifying/locating/mapping surface karst features and relevant attribute data.

The total (saturation) search is used for critical areas within cutblocks. This method uses high intensity search patterns (e.g., grids, concentric circles or lateral loops), with the intention of covering all ground within the field of view (e.g., 5–20 m spacing, depending on vegetation cover).

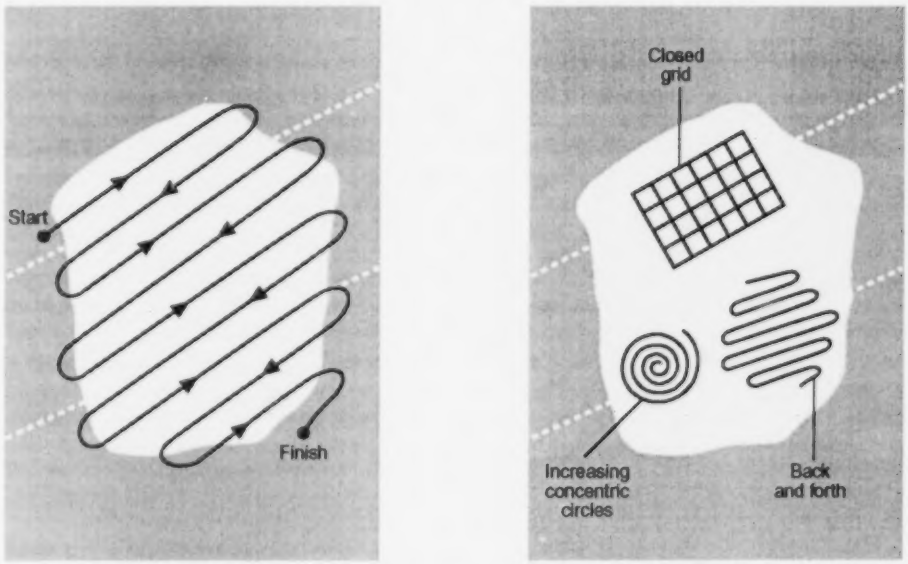
The advantages and disadvantages of the four ground searching techniques are more fully described in Appendix E.

Mapping of surface karst attributes requires judgemental and qualitative skills during data collection, visual estimation and compilation. Where ground searching typically gathers point data, mapping involves some level of interpretation and extrapolation during data collection to characterize certain linear or zonal patterns.



a) Linear (reconnaissance) transect search

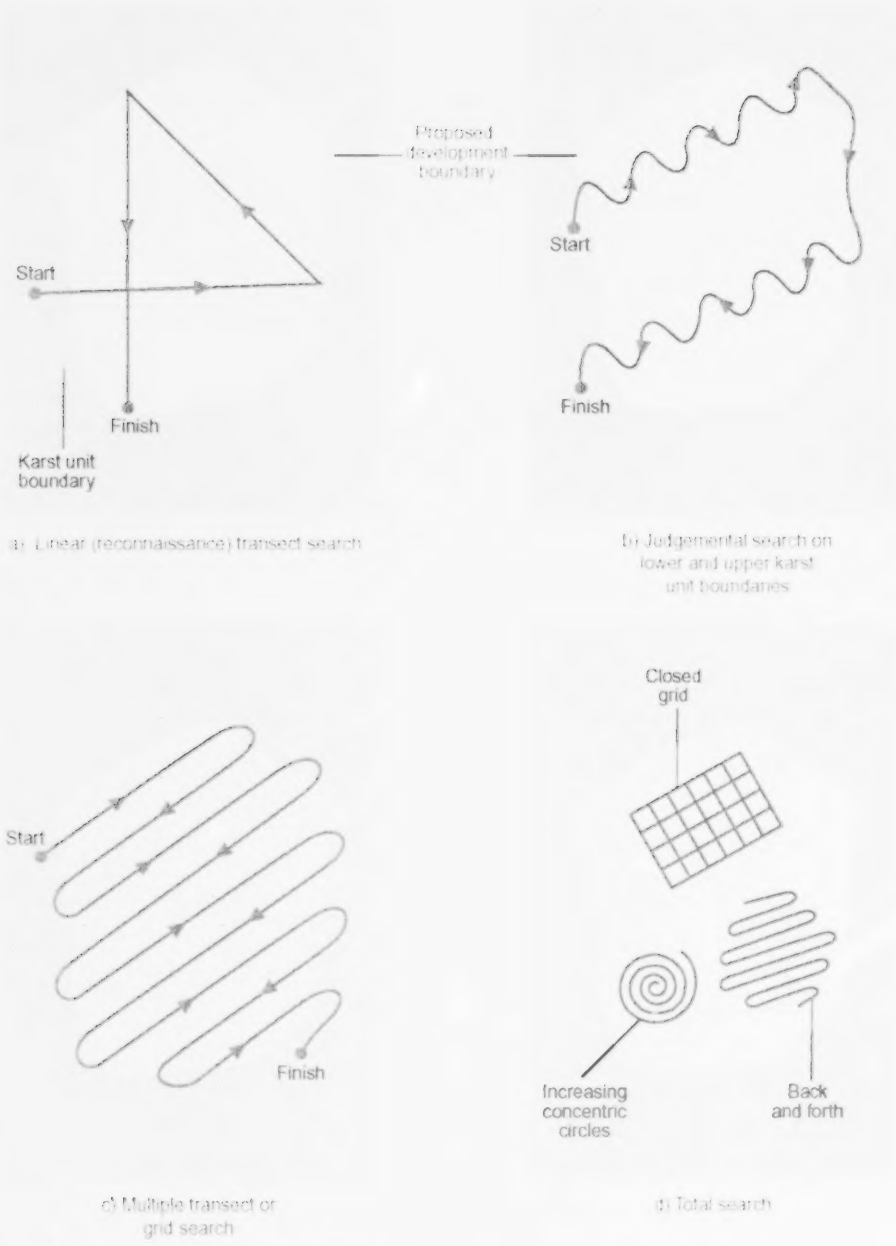
b) Judgemental search on lower and upper karst unit boundaries



c) Multiple transect or grid search

d) Total search

Figure 4.3. Ground searching techniques.



a) Linear (reconnaissance) transect search

b) Judgemental search on lower and upper karst unit boundaries

c) Multiple transect or grid search

d) Total search

Figure 4.3. Ground searching techniques

An important part of surface mapping at the KFA level is to determine the boundaries of karst polygons within the area of interest. (Note: in some cases, such as a small cutblock with only one polygon, a map may not be required.) Preliminary karst polygons might be obtained from previous planning-level karst inventory work or from the office review. These karst polygons are intended to represent areas of similar surface (and to some extent subsurface) karst attributes. The key karst attributes used to determine karst polygon boundaries during the field phase are epikarst development, surface karst feature density and subsurface karst potential; other attributes considered include soil type/thickness and karst roughness. Once the karst polygons have been defined, they can then be classified using the vulnerability assessment procedure outlined in Section 4.6.

4.3.3 Stream Evaluation

Streams that drain across or into karst areas require careful evaluation as they generally require site-specific prescriptions. Due to their complexity and linear nature, streams flowing on karst are not directly incorporated into the vulnerability assessment process, which is an area-based procedure. However, streams are a critical component of the karst system that need to be assessed, primarily because of the close hydrological links that can exist between the surface and subsurface.

The primary management objectives associated with streams are to maintain water quality and quantity, and limit the introduction of sediment and woody debris (large and small) into the subsurface within the range of natural conditions. Large woody debris and sediment can be transported downstream where it accumulates and clogs sink points. This can restrict water flow into the sink point and/or redirect flows to other subsurface openings or to the surface. Of particular concern is the introduction of fine sediment (e.g., silts, sands, clays) and fine organic material (e.g., needles, twigs, leaves) into subsurface openings or caves by way of streams that sink into the ground at distinct points (sinking streams) or lose water through a series of small openings, fractures or sink points (losing streams). These materials can coat underground surfaces, thereby impacting subsurface habitats and other cave resources or values. The slow decay rate associated with underground environments in British Columbia allows the organic component of this material to persist over long periods of time.

Two major considerations in the evaluation of streams are locating the points where water sinks underground, and determining the significance of the karst resources receiving the water (recipient features). Procedures for assessing streams are provided in Section 4.4.5.

4.3.4 Subsurface Inspection and Mapping

Subsurface inspection and mapping can be an important part of a KFA in areas where caves occur. Subsurface inspection and mapping is used to:

- assess caves for their significance;
- collect survey data to establish the three-dimensional location of the cave system with respect to the surface; and
- help determine the subsurface karst potential for an area (see Section 4.4.6).

When caves are encountered during a KFA, they will need to be inspected and classified to determine their significance in order to assist with appropriate management decisions. Caves can be dangerous[13] and/or sensitive environments. Steep cave entrances and interior passages

[13] For cave rescues and other emergencies, call the local RCMP or the PEP Emergency Coordination Centre at 1-800-663-3456.

should only be inspected and classified by experienced personnel. In many cases, field workers carrying out a KFA will not be qualified or suitably equipped to safely inspect caves, and individuals with specialized knowledge or training may need to be used for this task. The inspection and classification of caves is a detailed inventory in its own right, and is not described in this document. Personnel inspecting caves as part of a KFA should be referred to the *Cave/Karst Management Handbook for the Vancouver Forest Region* (BC Ministry of Forests, 1994) for guidance.

In some cases, surveying and mapping of caves is required to determine their three-dimensional location with respect to the surface prior to the initiation of road construction or timber harvesting (e.g., to establish the thickness of the ceiling and the underground orientation of the cave relative to the area of development). For some sites, cave maps may already be available through Forest Service district offices or caving organizations. Where caves are previously unmapped, surveying and mapping will need to be completed for at least those portions of the cave that underlie the area of proposed development. For relatively small caves, it may be practical to survey and map the entire cave at one time, even though it may extend somewhat beyond the area of proposed development. For larger cave systems, surveying and mapping only those areas that underlie the area of proposed development may be a more practical and cost-effective approach.

A set of accepted symbols endorsed by the International Speleological Union for mapping cave passages and features is provided in Appendix F. A coding key and classification card for caves from the *Cave/Karst Management Handbook for the Vancouver Forest Region* are also provided in Appendix F. A standard cave survey form is provided in Appendix G (Field Card #1).

Cave survey and mapping information can also be used to help determine subsurface karst potential ratings (see Section 4.4.6).

4.4 Methods for Identifying, Measuring and Evaluating Key Karst Attributes

This section provides details on how to identify, measure and evaluate karst attributes for a KFA. The key karst attributes considered in a KFA are:

- karst unit boundaries and geological characteristics (Section 4.4.1);
- distribution and intensity of epikarst development (Section 4.4.2);
- overlying soil thickness/texture and epikarst sensitivity (Section 4.4.2);
- location, types and density of surface karst features (Section 4.4.3);
- roughness of the karst surface (Section 4.4.4);
- streams and hydrology (Section 4.4.5);
- potential for caves and other subsurface cavities (Section 4.4.6); and
- occurrence of unique or unusual flora/fauna and/or habitat (Section 4.4.7).

Geomorphic hazards that could potentially impact the karst unit should be located, identified and briefly examined during a KFA (see Section 4.4.8).

4.4.1 Karst Unit Boundaries and Geological Attributes

Karst occurrences are the result of weathering and chemical processes that affect soluble carbonate bedrock (limestone, dolomite, marble) and, to a lesser extent, gypsum (see Section 1.2). The recognition of karst in the field is commonly done by observing the

various types of terrain features and surfaces that have resulted from karst processes, rather than directly from carbonate bedrock lithology. At the hillslope-scale, large features, such as a lack of surface drainage, sinkholes and exposed epikarst, are used to confirm the presence of karstified bedrock. At the outcrop-scale, karstified bedrock typically has rounded and light-coloured to gray surfaces, sometimes displaying distinctive solutional flutes or karren where sloped. Limestone is a relatively soft rock that can be easily scratched with a steel blade (marble and dolomite are less easily scratched). A standard test for confirming the presence of carbonate bedrock is to carefully place a few drops of dilute (10% molar) solution hydrochloric acid (HCl) on the rock (avoiding contact with skin or eyes). The acid readily effervesces (bubbles) with limestone and marble, and, to a lesser extent, with dolomite.

Recognizing and identifying the boundaries of karst units is an important part of a KFA, as it provides constraints on the extent of the inventory area. Karst unit boundaries can be determined in the field by obvious changes in terrain characteristics (as indicated above). Boundaries of karst units can also be determined by recognizing changes in outcrop types, as is typically done during geological mapping or by examining exposures along road cuts. Some basic understanding of geological processes and concepts is also useful in interpreting the boundaries of a karst unit, which can have layered, faulted or intrusive contacts with other bedrock types.

Characteristics of the bedrock geology can be used to determine more about the three-dimensional nature of a karst unit. These characteristics include bedrock lithology (of both the karst and adjacent bedrock units), and bedrock structures such as bedding planes, faults, folds and major joints (see Appendix B).

Once confirmed in the field, karst unit boundaries are delineated on the base map (see Figure 4.4).

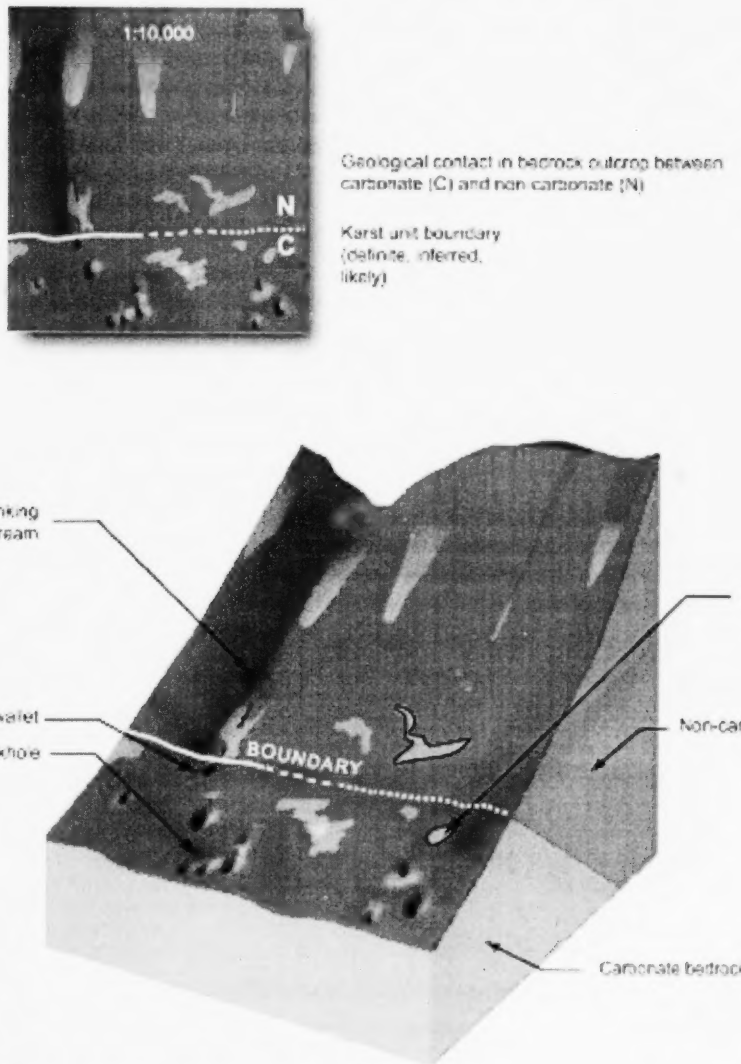


Figure 4.4. Karst unit boundary delineation.

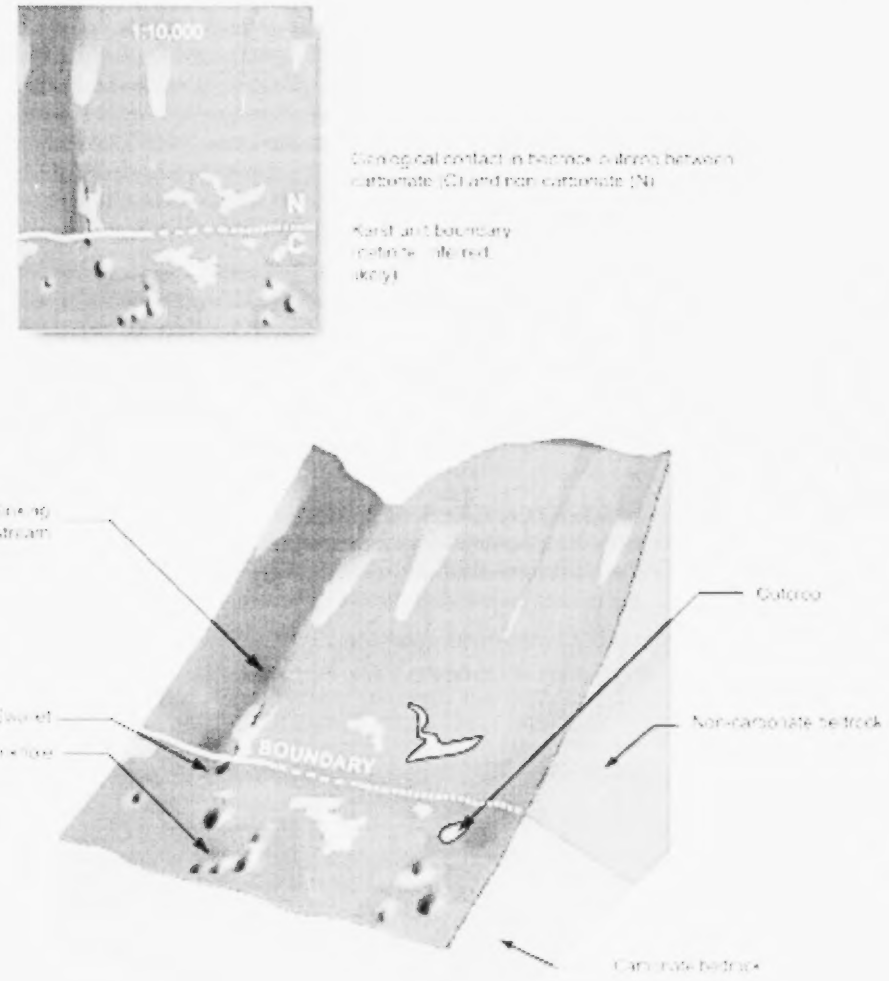


Figure 4.4. Karst unit boundary delineation.

4.4.2 Epikarst

Epikarst is a critical component of the karst system. Firstly, it allows for diffuse water flow and, in some cases, discrete water flow into the subsurface drainage system, allowing for the potential transfer of sediment and fine organic matter underground. Secondly, epikarst is at the sensitive vegetation/soil boundary of the karst system, where many of the surface solutional processes occur and which, if sufficiently disturbed, can lead to site degradation with the loss of soil into vertical openings.

A number of steps are required to determine epikarst sensitivity.[14] The first step is to estimate the level of epikarst development, the second is to determine the depth (and texture) of soil cover, and the third is to combine these two variables to determine an epikarst sensitivity rating.

Epikarst Development

Epikarst development is evaluated by measuring the two basic elements of epikarst—the average depth and frequency of small vertical intersection features or solutional openings[15] within specified size limits. Intersection features and solutional openings include karst joints, karst fissures, small grikes, karst clefts, solution pipes and small pits or shafts (see Appendix D). The level of epikarst development is most easily estimated from exposed epikarst surfaces with little or no soil cover.

To aid in determining an epikarst development rating, a depth versus frequency chart has been developed to visually estimate the level of epikarst development (see Figure 4.5). By using this chart in the field, a worker is able to approximate the level of epikarst development for the area being considered.

Calibration plots can be used to verify a worker's visual estimates of epikarst development. As workers become more experienced with using the visual chart, it should be possible to significantly reduce the number of calibration plots required.

Calibration plots for counting and measuring solutional openings in epikarst are established as circular modal plots of 5.64 m radius, encompassing 100 m^2 or 0.01 ha (see Figure 4.6). The plot centre is flagged and numbered, and the boundary marked in the field. The centre of the plot is geo-referenced to a known position.

For the evaluation of epikarst development (using either the visual chart or calibration plots), minimum and maximum size limits of solutional openings have been designated. To be counted as epikarst solutional openings, features should be well defined and have vertical or sub-vertical bedrock walls, with a minimum surface dimension (width, length or diameter of a plane formed by the surface opening) of 10 cm and a maximum surface dimension of 1.0 m. The depth of the solutional opening must be at least twice the minimum surface dimension. For example, if the minimum surface dimension is 10 cm, the depth must be greater than 20 cm, or the opening would not be counted.

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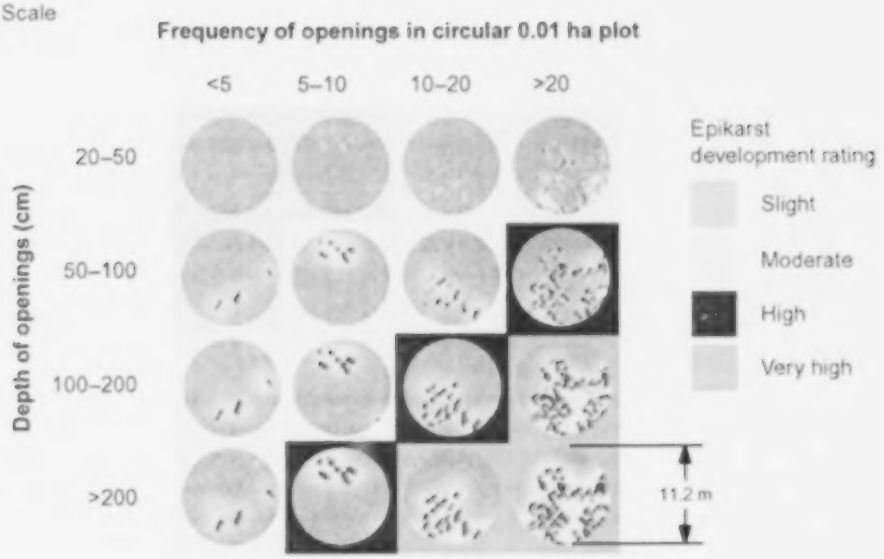
[14] 'Epikarst sensitivity' is defined as the susceptibility of epikarst and its overlying soil material to disturbance or change, and is a function of the level of openness or connectivity to the subsurface.

[15] A 'solutional opening' is defined as one that has vertical to sub-vertical walls, slightly rounded edges, and is the result of bedrock dissolution due to karst-forming processes.

Plan view

1:650 Scale



Perspective View

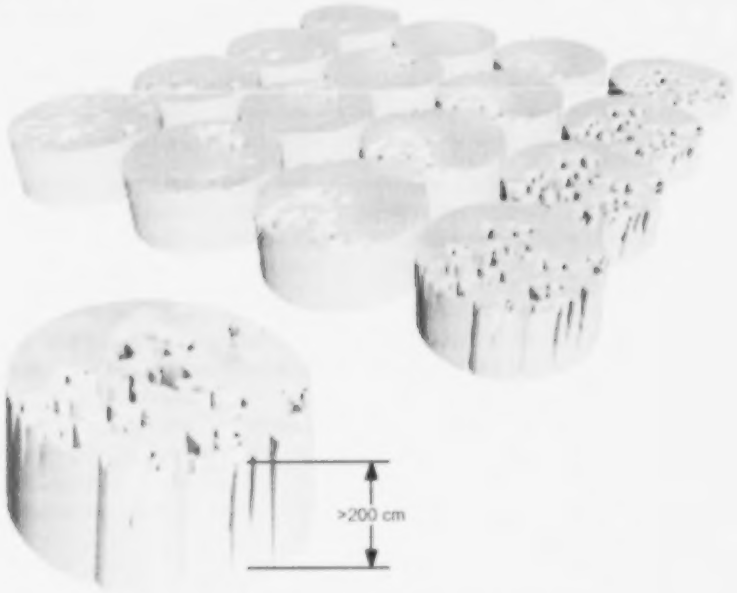


Figure 4.5. Visual chart for determining epikarst development rating.

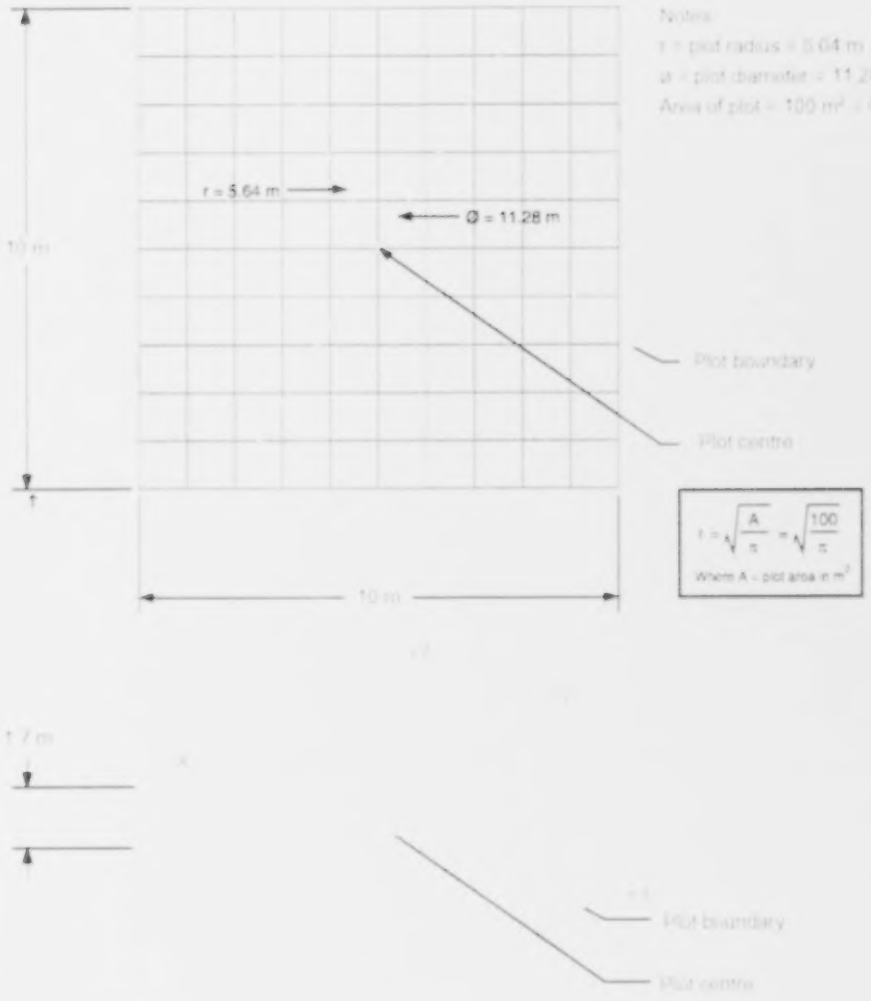


Figure 4.6. Calibration plot for determining epikarst development

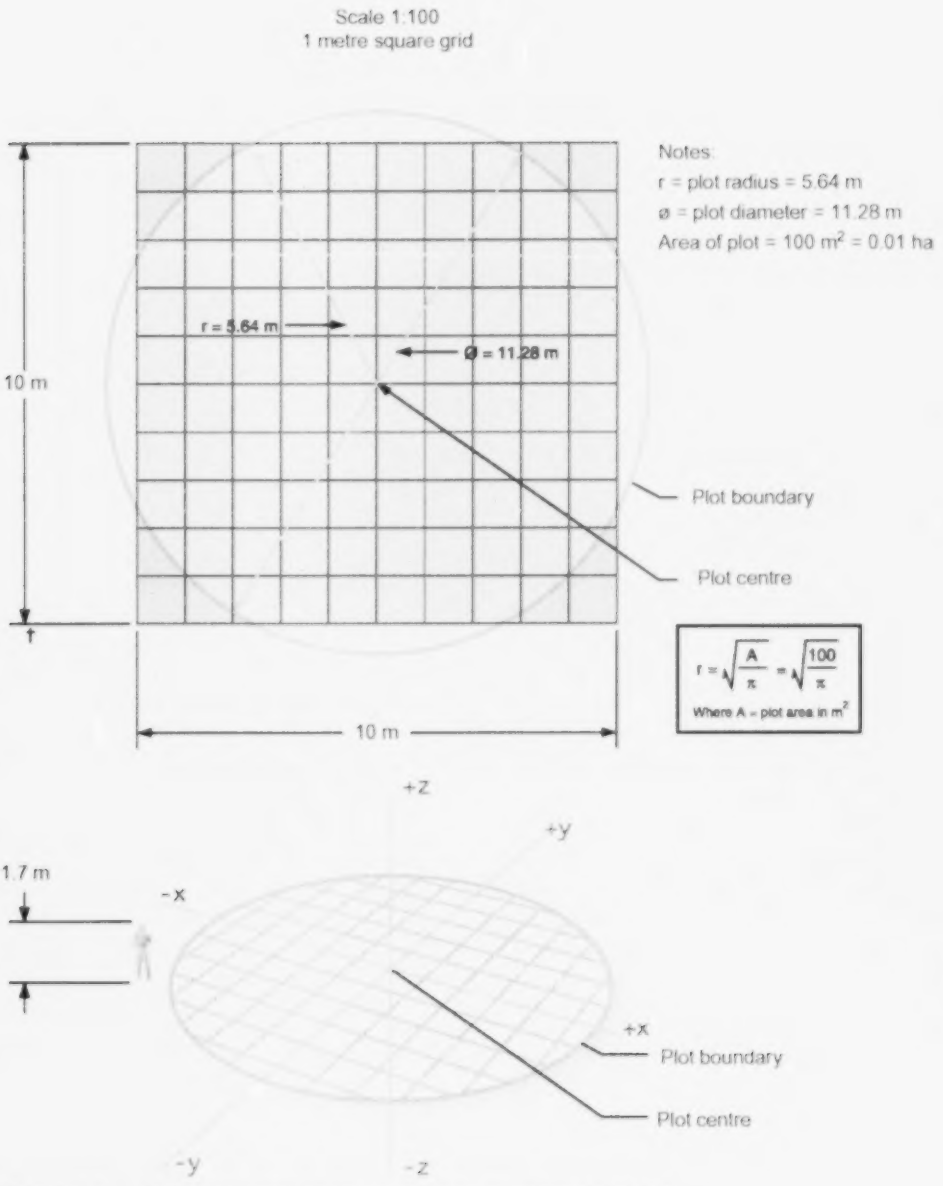


Figure 4.6. Calibration plot for determining epikarst development.

Solutional openings with a minimum surface dimension larger than 1.0 m are considered surface karst features and are not included in the evaluation of epikarst development (see Figure 4.8, p. 46). Calibration plots for epikarst development should not contain any surface karst features, nor should solutional openings take up more than 20% (20 m^2) of the plot area, as this would have a tendency to skew the results.

During an evaluation of epikarst development, it is possible to encounter nested epikarst openings of various sizes (i.e., one or more recognizable openings contained by another). In such a case, only the outer opening is considered. If two or more epikarst openings of roughly equal size coalesce, only the one combined opening is measured. If the interior bedrock separations are more than half of the height of the larger opening, the openings are measured separately.

The depth of a solutional opening is measured using a calibrated, metre-long steel probe, working from the edge of the opening to the lowest point below the surface, which might be the bottom of the opening or a layer of infilled material. (The length of the average arm is approximately one metre, thereby allowing for the measurement of depths up to 2 m, the maximum depth of a solutional opening included in an epikarst development evaluation.) The metre-long probe is made from heavy gauge (5 mm diameter) steel rod with a right angle bend at the top. Markings at 0.1 m intervals are indicated on the probe using a black indelible marker.

The average of the depth measurements for a calibration plot is recorded as one of four categories: 20–50 cm, 50–100 cm, 100–200 cm or >200 cm, while the number of openings is recorded as <5, 5–10, 10–20 or >20. These values are then combined using Figure 4.5 to arrive at a rating for epikarst development: slight, moderate, high or very high.

The procedure requires an integration of findings from the visual chart, supported by calibration plots where required, to arrive at an overall epikarst development rating for a particular karst polygon. If significant differences in epikarst development ratings are found within the polygon, there may be a need to further subdivide the polygon. Other karst attributes may also play a role in subdividing preliminary karst polygons (see Section 4.5).

Soil Thickness and Texture

Soil thickness in karst terrain can be highly variable at the site level, with thin soils on partially exposed solutional ridges, to thicker soil deposits in the intervening low areas. Soil thickness can also be highly variable where epikarst is not exposed at the surface. Average soil thickness is an integration of measurements from the hums and hollows.

Soil thickness and soil texture can be estimated using one or more of the following:

- natural exposures on the slope surface (e.g., windthrow);
- small hand pits excavated at representative locations within a karst polygon; or
- a steel probe.

When estimating soil thickness, the forest litter or duff layer is considered part of the overlying soil material. (In some cases, forest litter is the only material overlying epikarst.) There are six soil thickness categories: bedrock, <20 cm, 20–50 cm, 50–100 cm, 100–200 cm and >200 cm.

Procedures for identifying soil textures should follow those outlined in the *Terrain Classification System for British Columbia*. The identification of fine-textured and potentially erodible materials over well-developed epikarst is important, as it is relatively easy to disturb this type of material during surface activities (e.g., cable yarding). For the purpose of this

procedure, fine-textured soils of concern are typically those comprised of predominately silt and sand fines with <20% coarse fragments. If the presence of fine-textured soil is apparent, this modifying factor is incorporated into the epikarst sensitivity rating (see below).

Determination of Epikarst Sensitivity

Epikarst sensitivity combines the two main variables of epikarst development and soil thickness, as well as a modifying factor for soil texture. Table 4.1 uses the epikarst development rating versus an average soil thickness to come up with four ratings for epikarst sensitivity: low, moderate, high and very high. If an erodible, fine-textured soil is present, the rating for epikarst sensitivity is increased by one category (see Section 4.6.1 and Figure 4.14, p. 59).

Table 4.1. Rating table for epikarst sensitivity

Epikarst development rating	Average soil depth (cm)					
	>200	100–200	50–100	20–50	<20	Bedrock
Slight	Low	Low	Low	Low	Low	Low
Moderate	Low	Low	Low	Moderate	Moderate	Moderate
High	Low	Low	Moderate	Moderate	High	High
Very High	Low	Low	Moderate	High	Very High	Very High

4.4.3 Surface Karst Features

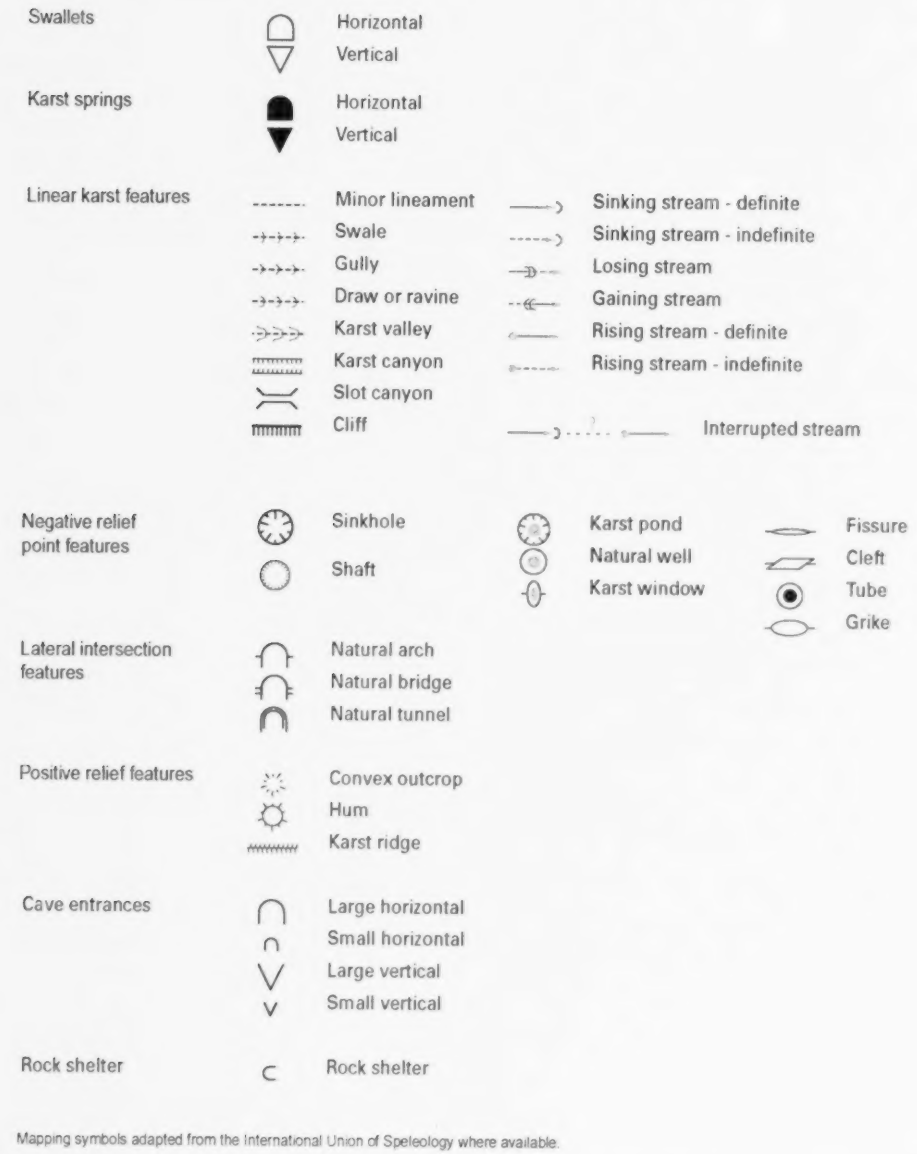
An important part of a KFA is to examine and evaluate discrete surface karst features (e.g., sinkholes, cave entrances, swallets) within the area of interest. The main goals of these activities are to:

- locate and classify surface karst features;
- determine the significance of surface karst features; and
- collect data for estimating the density of surface karst features.

The main types of surface karst features are:

- cave entrances;
- linear features (bluffs, canyons);
- positive relief features (hums or hillocks);
- negative relief features (e.g., sinkholes, grikes);
- lateral features (e.g., rock arches or bridges); and
- insurgences and emergences (swallets and karst springs).

Specific details on surface karst features that should be located and classified are included in Appendix D. A field card for recording surface karst feature data is provided in Appendix G (KFA Field Card #2). Appropriate mapping symbols for surface karst features are provided in Figure 4.7.



Mapping symbols adapted from the International Union of Speleology where available.

Figure 4.7. Surface karst feature classification scheme and mapping symbols.

Locating and Classifying Surface Karst Features

The ground searching techniques outlined in Section 4.3.2 are used to locate surface karst features. The features are classified using the system described in Appendix D.

Once located, the more notable surface karst features are marked in the field with coloured flagging and geo-referenced. Compass and chain measurements are taken from the marked feature to a nearby reference point (e.g., road station or falling corner). Where site conditions allow, GPS can be employed to geo-reference features. Accuracy to the nearest 10 m is considered adequate for most surface karst features (e.g., 2 mm at the 1:5000 scale).

Determining the Significance of Surface Karst Features

Surface karst features found during the ground search are evaluated to determine their significance. This determination is largely qualitative and requires a level of judgement. A number of criteria are considered, including dimensions, biological importance, scientific values, abundance/rarity, connectivity with the subsurface, hydrological characteristics, recreational appeal and cultural values. The procedure for determining the significance of surface karst features is described in detail in Appendix C. A field card for evaluating the significance of surface karst features is provided in Appendix G (KFA Field Card #3).

Surface karst features that are not obviously sensitive or technically difficult to access (e.g., not requiring ropes or special climbing equipment) are assessed to determine their significance and connectivity to the subsurface. Sensitive or technically difficult surface karst features should only be examined by personnel with appropriate training and experience. The degree of connectivity is used to help in the determination of a subsurface karst potential rating (see Section 4.4.6).

Possible cave entrances should be examined to establish if the surface opening is part of a cave. If a possible cave entrance leads to a cave, a cave inspection is required (see Section 4.3.4).

Estimating the Density of Surface Karst Features

Surface karst feature density is the estimated number of negative relief features (e.g., sinkholes, grikes) per hectare, and is expressed as skf/ha. For the purpose of determining surface karst feature density, a surface karst feature is one with a surface dimension (length, width or diameter of a plane formed by the surface opening) greater than 2 m and a depth greater than 2 m[16] (see Figure 4.8).

The five range categories used for estimating the density of surface karst features are:

- 0 skf/ha;
- 1–5 skf/ha;
- 5–10 skf/ha;
- 10–20 skf/ha; and
- >20 skf/ha.

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[16] Features with surface dimensions within the 1–2 m range represent the continuum that exists between countable epikarst openings (<1 m) and what are considered surface karst features for this procedure (>2 m). These kinds of features can be mapped and evaluated individually, or as a group of small features, but are not used in the determination of either epikarst development or surface karst feature density (see Figure 4.8).

	Diameter	Depth	Length/width
To qualify for epikarst vertical openings	>10 cm <100 cm	>20 cm	>100 cm
To qualify for surface karst features	>100 cm	>200 cm	>100 cm
To qualify for density calculation for surface karst features	>200 cm	>200 cm	>200 cm

Epikarst

Continuum

Surface karst features

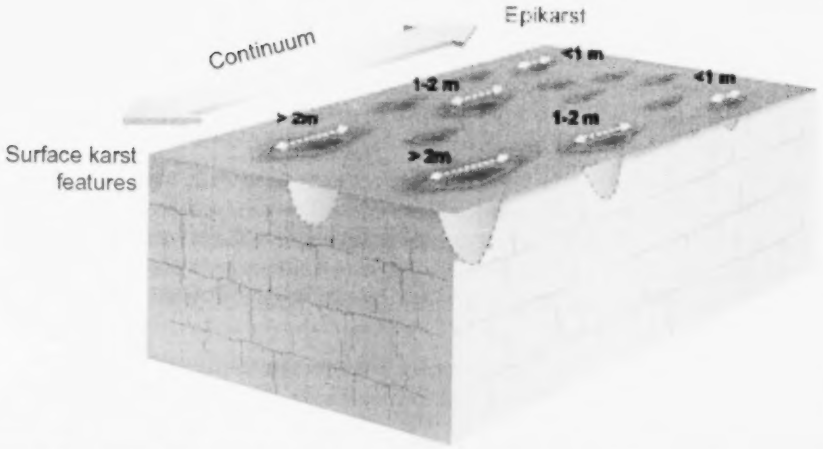

Figure 4.8. Classification of vertical solutional openings and the continuum between epikarst features and surface karst features.

	Diameter	Depth	Length/width
To qualify for epikarst vertical openings	>10 cm <100 cm	>20 cm	>100 cm
To qualify for surface karst features	>100 cm	>200 cm	>100 cm
To qualify for density calculation for surface karst features	>200 cm	>200 cm	>200 cm

Epikarst

Continuum

Surface karst features

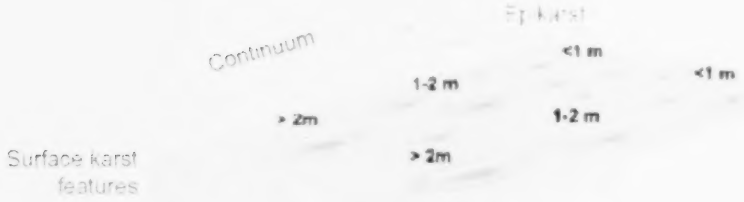

Figure 4.8. Classification of vertical solutional openings and the continuum between epikarst features and surface karst features.

Density ranges for surface karst features are estimated directly in the field using a visual chart (Figure 4.9). Ranges can also be estimated after the features are plotted on the base map. Calibration plots, similar to those described for epikarst development (see Section 4.4.2), can be used to verify visual estimates of surface karst feature density. These calibration plots have a radius of approximately 56.4 m and encompass 1.0 ha (see Figure 4.10). Surface karst features within the plot are counted and recorded in the appropriate range category.

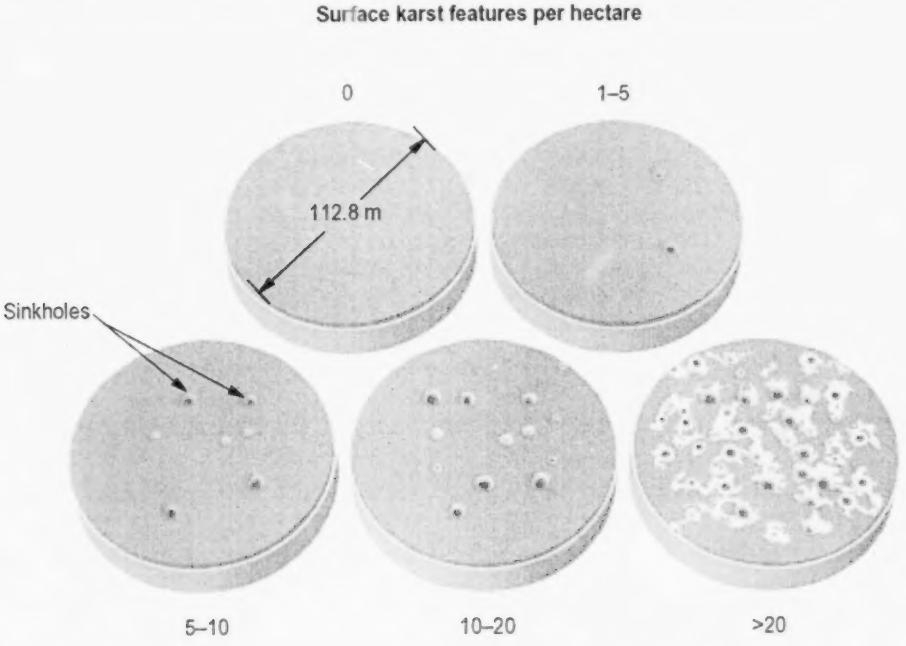

Figure 4.9. Visual chart for determining the density of surface karst features.

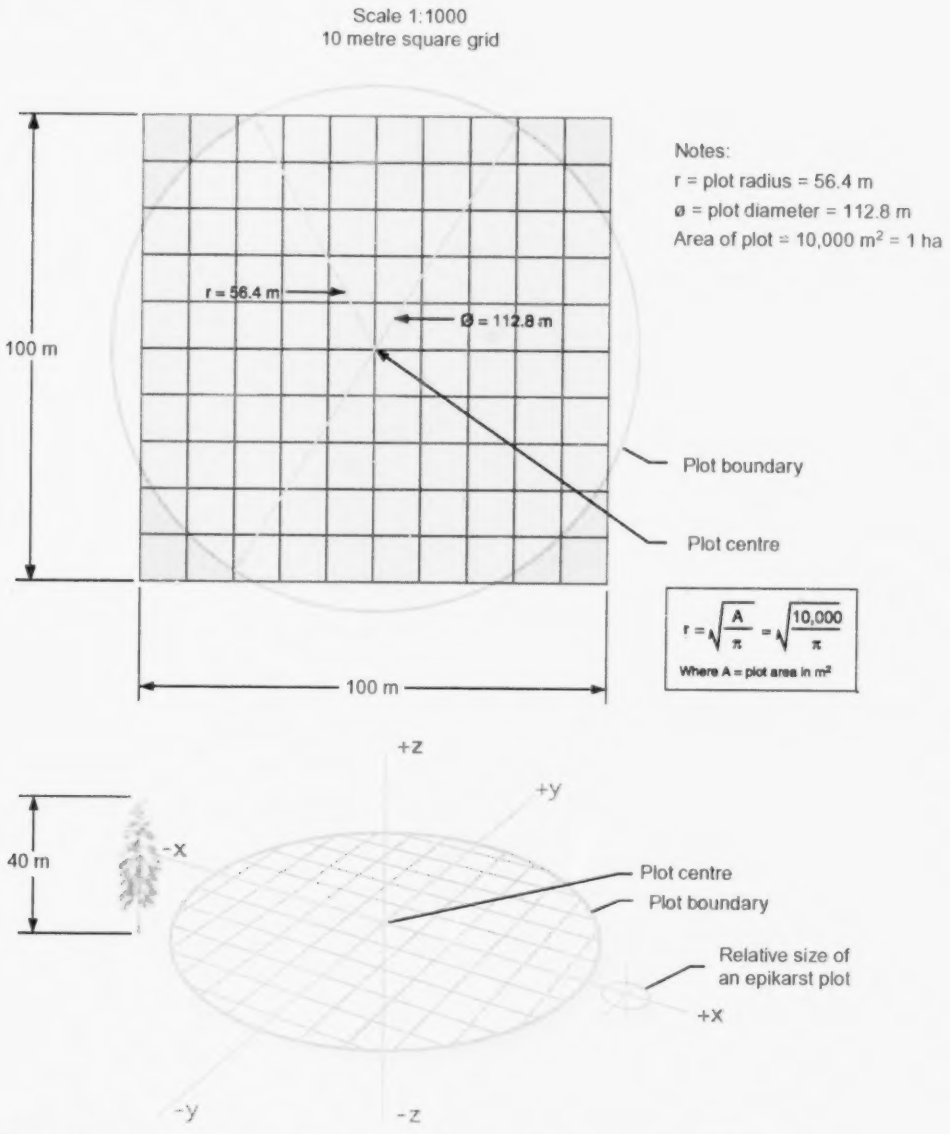

Figure 4.10. Calibration plot for determining surface karst feature density.

Density ranges for surface karst features are estimated directly in the field using a visual chart (Figure 4.9). Ranges can also be estimated after the features are plotted on the base map. Calibration plots, similar to those described for epikarst development (see Section 4.4.2), can be used to verify visual estimates of surface karst feature density. These calibration plots have a radius of approximately 56.4 m and encompass 1.0 ha (see Figure 4.10). Surface karst features within the plot are counted and recorded in the appropriate range category.

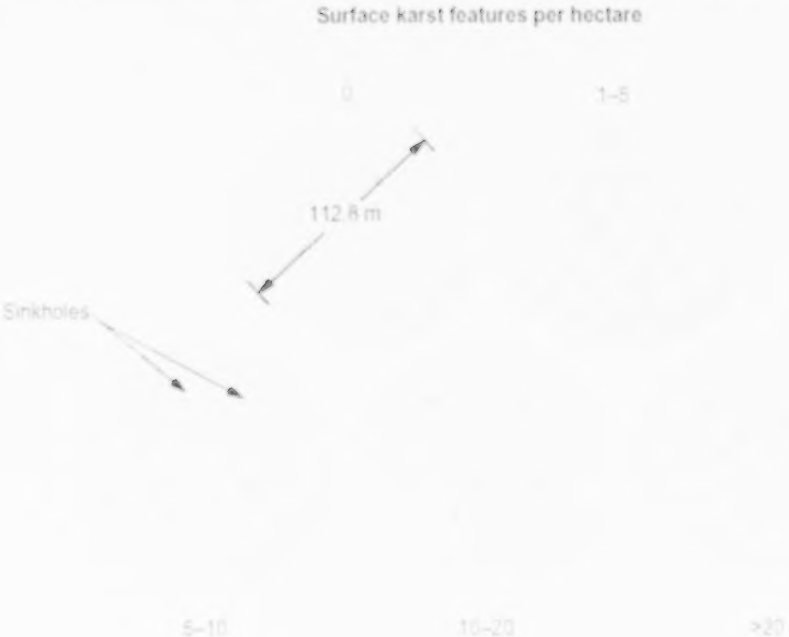

Figure 4.9. Visual chart for determining the density of surface karst features.

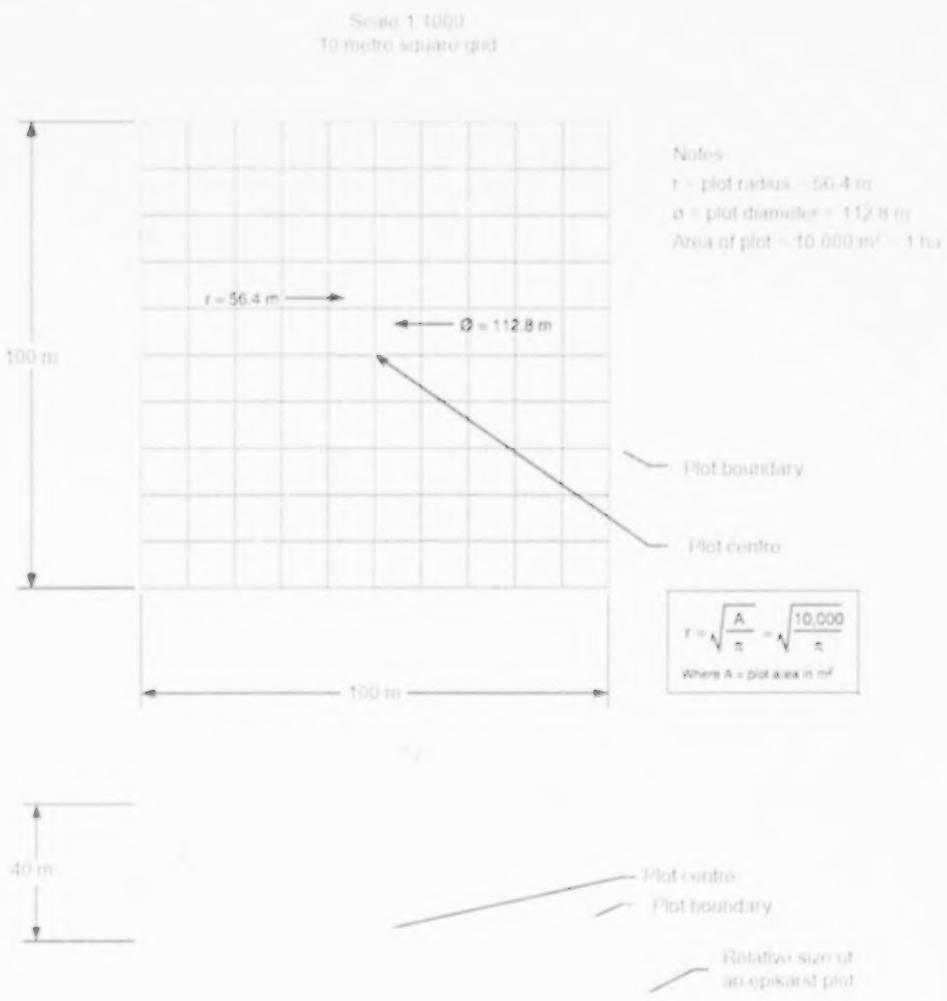

Figure 4.10. Calibration plot for determining surface karst feature density.

Table 4.2 combines surface karst feature density ratings with epikarst sensitivity ratings (see Section 4.4.2) to determine an overall rating for surface karst sensitivity, which is used in the vulnerability assessment procedure in Section 4.6.1.

Table 4.2. Rating table for surface karst sensitivity

Epikarst sensitivity rating	Surface karst feature density				
	0	1–5	5–10	10–20	>20
Low	Low	Low	Mod.	High	High
Mod.	Low	Mod.	Mod.	High	High
High	Mod.	Mod.	High	High	Very High
Very High	Mod.	High	High	Very High	Very High

4.4.4 Karst Roughness

Karst roughness is a function of the inherent characteristics of a karst surface (primarily the result of solutional weathering and glaciation) and the overlying soil cover. It is used as a modifying factor to assist in evaluating the unevenness or irregularity of the overall karst surface, which can be an indicator of the level of karstification and an indirect indicator of subsurface karst potential.

The term 'karst roughness' describes the general character and planar distribution of both epikarst zones and surface karst features, similar to the karst micro-topography codes used at the planning level (see Table 3.3). Karst roughness is determined at a broader scale than epikarst development ratings, and addresses positive relief features, which are not captured in epikarst development ratings or estimations of surface karst feature density. A rating for karst roughness considers the proportion of positive relief features to negative relief features (i.e., hums to hollows) and their relative distribution over a particular area. Figure 4.11 provides a visual method for rating karst roughness from low to very high.

The roughness factor is used to modify the surface karst sensitivity rating in the vulnerability assessment procedure (see Section 4.6.1 and Figure 4.14, p. 59). A karst roughness rating of high or very high would raise the surface karst sensitivity rating by one category.

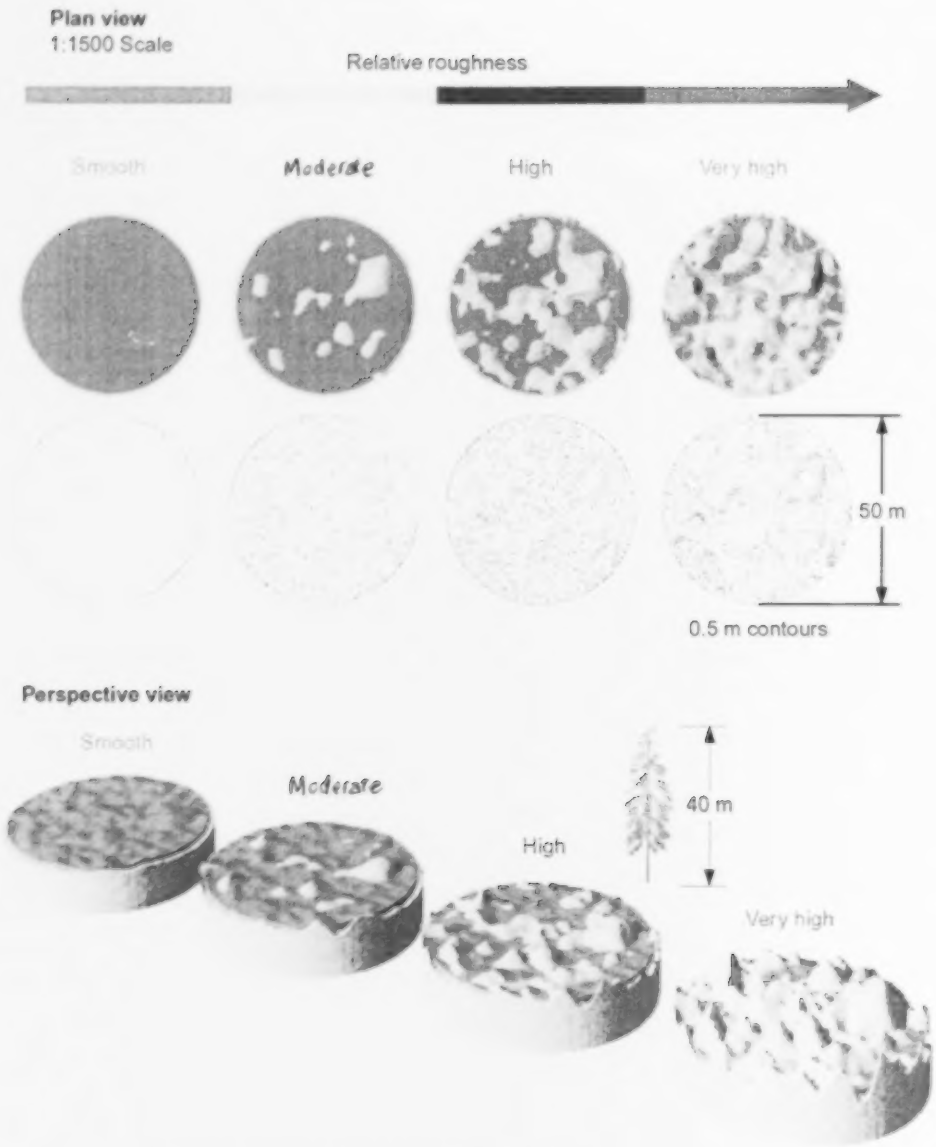

Figure 4.11. Visual chart for determining karst roughness.

4.4.5 Streams and Hydrology

A stream is 'a water course with a continuous channel of more than 100 metres' (Forest Practices Code). In karst terrain, it is recognized that a stream channel is continuous even after it sinks into the bedrock to flow underground. This makes the identification and evaluation of streams flowing on karst somewhat different from streams flowing on non-karst terrain. Flows along streams occurring on karst can be perennial, ephemeral or intermittent.

Stream Types

A variety of stream types can occur on karst terrain:

Surface streams – streams that flow in surface channels with minimal or no water loss to the subsurface.

Sinking streams – streams that disappear underground at a distinct sink point or swallow hole.

Losing streams – streams that gradually lose water through an unconsolidated alluvial channel bed, or through a series of small openings, fractures or sink points.

Interrupted streams – streams where the flow sinks into the subsurface and returns to the surface with no apparent loss of overall flow.

Gaining streams – streams that receive additional water from underground sources.

Rising streams (springs) – underground streams that emerge at the surface at a spring.

Figure 4.12 illustrates the various types of streams found on karst terrain.

Evaluating and Mapping Streams

Where the location and extent of the stream is previously unknown, a stream survey is required to record and geo-reference stream characteristics. If a stream survey has been previously completed, examination of the stream at various locations along its length should be sufficient to determine and record its characteristics.

Stream survey procedures require streams to be broken into reaches. A stream reach is defined as a portion of the stream that has relatively consistent characteristics, including channel width, gradient, side wall slope/length, channel sediment and side wall soil type/material. Procedures for determining stream reaches, channel width, depth and gradient are included in the FPC *Fish Stream Identification Guidebook*. For streams associated with karst, characteristics such as sink points, losing or gaining segments, and springs, will influence the location of reach breaks.

The identification of sinking and losing streams is one of the primary tasks associated with stream assessments on karst terrain, since these types of streams have the potential to transport sediment and debris into sensitive subsurface environments. Sinking streams commonly occur along the upper boundary of a karst unit, while losing streams can occur at any location where the water can seep into the karst.

Continuous surface streams, sinking streams and springs are readily apparent in the field. Losing streams can be identified by locating the small features where the water flows underground, or by observing a sudden drop in the volume of stream flow. Gaining streams can be identified by locating springs discharging flow into the stream from the side banks, or by observing a sudden increase in the volume of stream flow.

All sink points, losing or gaining segments, and springs should be recorded, geo-referenced and plotted on the map. Mapping symbols for stream types and hydrological features are provided in Figure 4.7.

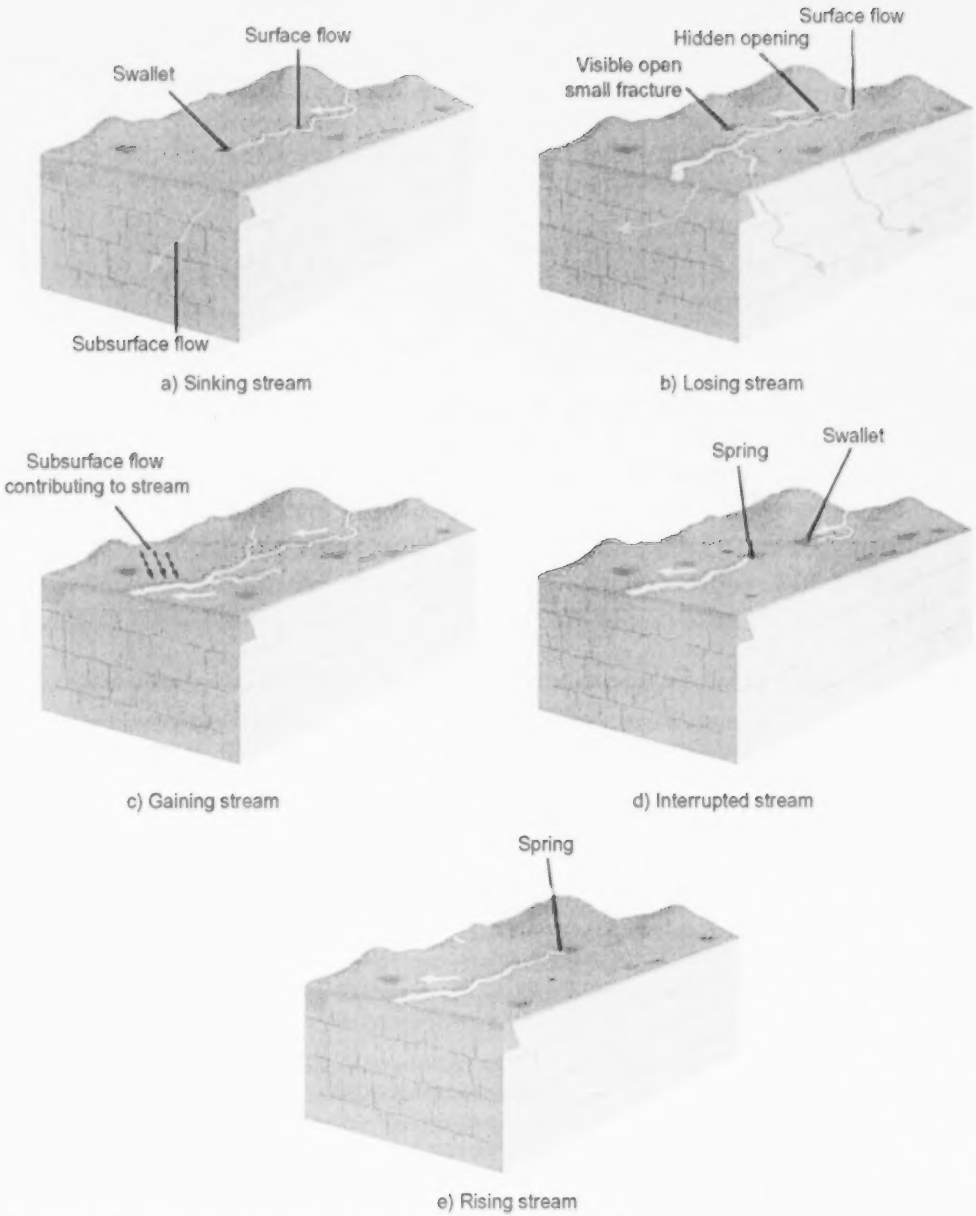

Figure 4.12. Stream types and characteristics on karst terrain.

Stream Assessment Distances

Stream assessment distances are based on the width of the stream, which is an indicator of the transport potential of the stream channel. Minimum width thresholds are different for streams flowing on karst (1.0 m) compared to those flowing over non-karst (1.5 m). This is to account for the sensitivity of karst to the transport of fine particulate matter into subsurface environments, and also considers the tendency of streams flowing over karst to incise into the soluble bedrock, creating somewhat deeper channels.[17]

- Stream width <1.0 m (karst) or <1.5 m (non-karst): assess the stream along its entire length within the proposed area of development, and for a minimum of 250 m downstream of the development boundary or the point where the stream flows off karst terrain, whichever is shorter.
- Stream width 1.0–3.0 m (karst) or 1.5–3.0 m (non-karst): assess the stream along its entire length within the proposed area of development, and for a minimum of 500 m downstream of the development boundary or the point where the stream flows off karst terrain, whichever is shorter.
- Stream width >3.0 m: assess the stream along its entire length within the proposed area of development, and from the development boundary downstream to the last contact with carbonate bedrock. For streams of this size, the assessment should be able to be conducted predominantly as an office exercise using bedrock geology maps, air photos, existing field knowledge and local knowledge of the area, etc.

Determining the Significance of Recipient Features

Where a stream assessment identifies a sinking or losing stream, the recipient feature must also be assessed to determine its significance in order to assign appropriate management prescriptions. Procedures for determining the significance of surface and subsurface karst features are described in Section 4.3.4 (Subsurface Inspection and Mapping), Section 4.4.3 (Determining the Significance of Surface Karst Features) and in Appendix C.

Dye Tracing and Collection of Other Karst Water Data

Dye tracing is an important tool for investigating the subsurface hydrology of karst systems. Details on dye tracing procedures are outlined in Section 3.3.4 and can be found in Stokes and Griffiths (2000) and the *Groundwater Tracing Handbook* (Aley, 1999).

A number of other data measurements (e.g., conductivity, pH, temperature, dissolved oxygen content and flow rate) can be collected along streams or at sinking/emerging points to provide additional information on the karst hydrological system. Conductivity (or specific conductance) is probably the most useful information, particularly for identifying and mapping the presence of karst waters, and in the design and interpretation of dye tracing results (see Stokes, Aley and Griffiths, 1998). Specific conductance measures the ability of water to conduct electricity and is measured in micromhos/cm. In general, the longer water has been in contact with carbonate bedrock, the greater its specific conductance. Typically, waters occurring within or downstream of karst areas give high conductance values (e.g., >80 micromhos/cm), while waters draining non-karst areas give lower values

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[17] The procedures in this section have not been field tested, and the processes involved with the movement of fine particulate matter in streams flowing into subsurface karst openings is not well understood in British Columbia. Further research into these processes is required. It is recommended that the evaluation of streams on karst terrain be undertaken with an adaptive management approach, particularly with regard to stream assessment distances.

(e.g., <20 micromhos/cm). High or low conductance values can also give some indication as to whether a deep or shallow hydrological system is present—higher values indicate a deeper system. A standard lightweight conductivity meter, such as one used for water environmental studies, can be used for this purpose. Some calibration of the instrument is usually required, and it is typically placed in flowing water for 20–30 seconds for consistent measurements.

The use of a pH meter can be useful for determining if water has been in contact with karst. Karst waters typically have pH values of 7–8; however, readings can be slightly lower if acidic waters from non-karst bedrock or organic-rich areas (e.g., upland swamps) have been introduced. Measurements of pH can also be important for the analysis of dye tracing data.

Water temperature measurements can be useful under certain conditions, but can be affected by localized variables such as snow melt or microclimatic changes along the stream. During hot weather conditions, water temperature measurements can be useful for identifying water derived from karst springs, as temperatures are likely to be cooler than the surrounding surface flows.

Flow rate estimates can be useful at sinking or emerging points (springs) to monitor changes in water movement over time, both seasonally and long term. Knowledge of flow rates is important for dye tracing tests. Flow rates can be estimated using channel cross-sectional areas and flow velocities. However, since flows in karst systems can be highly variable, measurements are required at a number of stages or times throughout the year to obtain accurate information.

4.4.6 Estimating Subsurface Karst Potential

Estimating subsurface karst potential is an important part of a KFA. Attributes used to determine subsurface karst potential include, but are not limited to:

- bedrock lithology;
- sinking/rising streams;
- known cave entrances or passages;
- surface karst features with evidence of connectivity to the subsurface;
- evidence of subsurface water flow (e.g., high conductivity readings in surface streams);
- favourable topographic position (e.g., benches below high relief recharge slopes); and
- a high karst roughness rating.

Subsurface karst potential ratings can be determined qualitatively by assessing surface karst attributes in the area of interest and/or from experience gained on similar karst terrain. Table 4.3 provides criteria for determining subsurface karst potential. Where subsurface inspection and mapping has been carried out, this information can be used to confirm or adjust subsurface karst potential ratings.

Subsurface karst potential ratings—low, moderate or high—add the third dimension to karst polygons, and are used in the karst vulnerability procedure (see Section 4.6.1) to provide a final karst vulnerability rating (refer to Figure 4.14, p. 59).

Table 4.3. Criteria for determining the subsurface potential rating

Subsurface potential	Geology	Topography	Hydrology	Knowledge of karst
Low	Impure carbonates	Lower relative elevation as compared to surrounding terrain	No evidence of water sinking or emerging	No known subsurface karst in bedrock unit
Moderate	Moderately pure carbonates	Steep slopes with small breaks	Minor springs/ losing creeks	Known caves in bedrock unit at similar sites
High	Pure carbonates	Benches or breaks in slopes below likely recharge areas	Swallets and springs; no surface drainage	Known caves within area of interest

4.4.7 Unique or Unusual Karst Flora and Fauna

The identification of unique or unusual karst flora or fauna during a KFA can be carried out by either identifying individual species or by recognizing favourable habitats (see Table 3.8). The recognition of karst biota by individual species may require specialized expertise and a detailed knowledge of plant and animal taxonomy (see Tables A1 and A2 in Appendix A). This is beyond the scope of most workers completing a KFA. A limited number of karst flora and fauna experts, mainly associated with government agencies, are available for consultation when and if the need arises (see Table A3 in Appendix A).

In general, suitable habitats for karst flora in forested (closed canopy) terrain, particularly along the coast, are those that are moist, shaded and with shallow soils. Examples of these types of habitats include zones of well-developed epikarst, solutional grike fields, along karst bluffs or canyons, and in and around large and/or deep sinkholes, swallets, springs and cave entrances. Karst flora can also be found in open canopy sites, both on forested slopes and at higher elevations (subalpine/alpine locations). These sites are typically well drained, with thin soils over carbonate bedrock, and are exposed to sunlight. Sites such as these can display a considerable diversity of karst-related flora. Karst springs and calcium-rich seeps (e.g., tufa) can provide very distinctive sites for karst-specific flora (e.g., Giant Helliborine Orchids, *Epipactis gigantea*).

During a KFA, the main focus for identifying karst fauna is on the surface and, in some cases, the twilight zone of caves and other cavities. Inventory of fauna in the dark zone of karst cavities and caves is a highly specialized field, and beyond the scope of this document. The publication, *Caves and Cave Life*, by P. Chapman (1993), provides a straight forward reference on cave and karst fauna.

One of the principal mammals associated with karst caves are bats. Bats are known to use caves for maternity and hibernation colonies in a number of locations in British Columbia (e.g., Weymer Creek Caves on Vancouver Island). Standards for conducting bat surveys are outlined in *Inventory Methods for Bats* (RIC, 1998). Other mammals, such as black-tailed deer, weasels, marten and shrews, are also known to use karst openings for habitat (S. Rasheed, pers. com., 2000).

Most insect associations with karst are confined to cavities and caves, or springs. However, certain moths and butterflies are known to associate with limestone surfaces where greater plant

diversity is present. For example, the butterfly species *Boloria natazhati* is specifically linked to limestone terrain in the northern interior of British Columbia (C. Guppy, pers. com., 2000).

In British Columbia, salmon and/or trout have been observed in karst caves on Vancouver Island, Moresby Island and Princess Royal Island, but the nature of this association has not been scientifically investigated. However, there is documented evidence for an increase in productivity and population size of Coho salmon in karst terrain in southeast Alaska (Bryant et al., 1998).

When unique or unusual karst biota or favourable habitats are identified during a KFA, the location of the site is recorded and mapped, along with a detailed description of what was encountered. For assistance in identifying or confirming species, contact the Conservation Data Centre, Ministry of Environment, Lands and Parks, or one of the experts listed in Table A3 in Appendix A.

In terms of karst vulnerability, if karst flora/fauna or habitat sites are considered significantly large, unusual or rare, they are utilized to influence the vulnerability rating of a karst polygon by increasing it at least one or possibly two levels (see Section 4.6.1 and Figure 4.14).

4.4.8 Geomorphic Hazards

During a KFA, geomorphic hazards that could potentially impact the karst area or unit of interest should be identified. These hazards can be the result of natural disturbances or man-made activities, and primarily include those hazards related to landslides, soil erosion and sediment transport, windthrow, and burned areas (see Appendix B).

The location, type and possible extent of geomorphic hazards are recorded, potential consequences to the karst unit assessed, and the need for further investigation determined. It is not the intent of a KFA to fully evaluate geomorphic hazards, but rather to identify them for evaluation by others with experience in this area (e.g., geoscientists or geotechnical engineers). Procedures for evaluating geomorphic hazards, such as landslides and soil erosion, are included in the *Gully Assessment Procedures Guidebook*, the *Hazard Assessment Keys for Evaluating Site Sensitivity to Soil Degrading Processes Guidebook*, and the *Mapping and Assessing Terrain Stability Guidebook*. Procedures for windthrow evaluation are included in the *Windthrow Handbook for British Columbia Forests* and in a recent paper on windthrow risk by Mitchell (1998).

Information collected on geomorphic hazards is not included in the vulnerability assessment process; however, it is recorded for consideration in management decisions (see KFA Field Card #4 in Appendix G).

4.5 Refinement of Karst Polygon Boundaries

Preliminary karst polygons can, in most cases, be delineated during the office review portion of a KFA (see Section 4.2). The key surface karst attributes and values used to refine the boundaries of preliminary karst polygons are epikarst development, soil thickness, surface karst feature density and, if required, karst roughness (see Figure 4.13). It is not intended that individual karst polygon boundaries be determined accurately for each karst attribute, but rather they be integrated to develop one boundary that represents an area of karst with similar characteristics. This type of integration process is similar to what is carried out for any mapping procedure (e.g., terrain or terrestrial ecosystem mapping). The estimation of subsurface karst potential should consider the openness of the karst beneath the polygon, rather than be used to delimit the polygon boundaries. In rare circumstances (e.g., an area

underlain by well-mapped cave passages), the subsurface potential rating might be used to help determine the polygon boundaries.

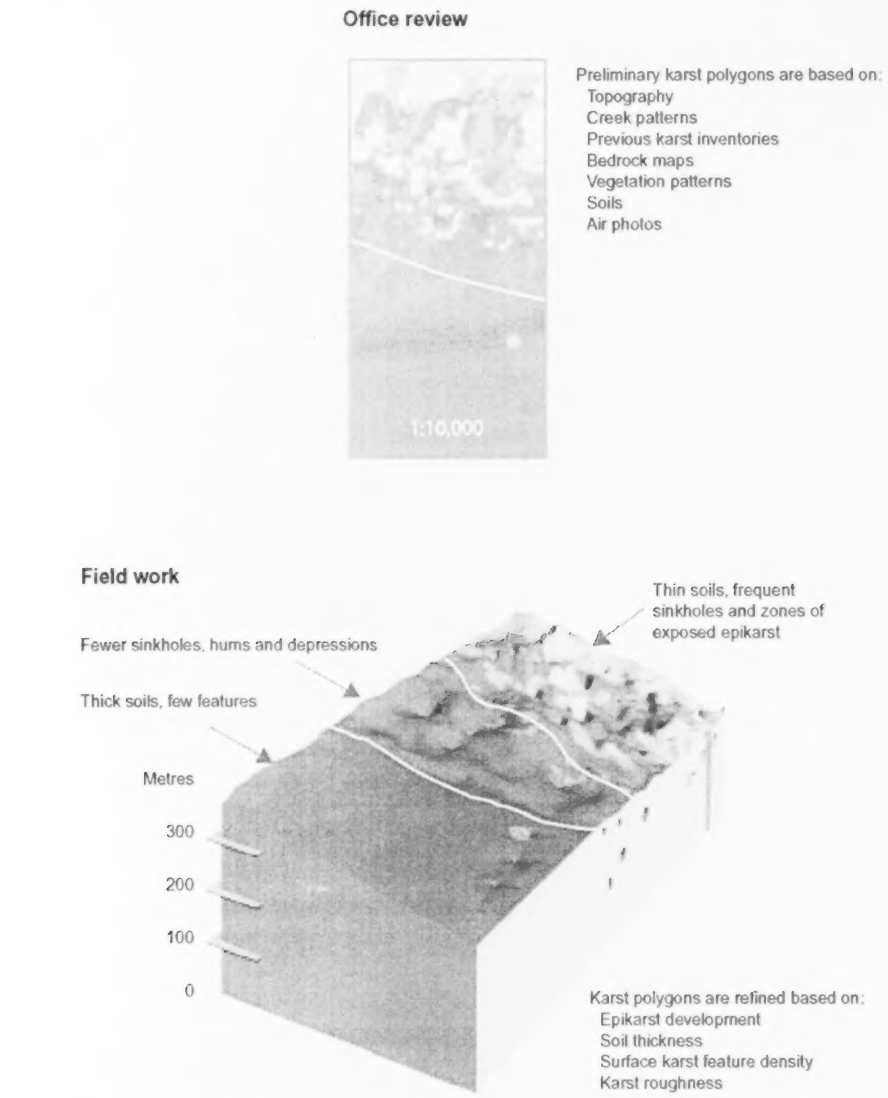

Figure 4.13. Example of karst polygon delineation and refinement.

4.6 Karst Vulnerability Assessment

The karst vulnerability assessment is the final part of a KFA, and provides the critical linkage between the inventory work and the recommended management prescriptions outlined in the *Karst Management Handbook for British Columbia*. The underlying goal of the karst vulnerability assessment process is to qualitatively integrate the surface and subsurface data collected during the KFA to derive a vulnerability rating for a particular karst polygon. This is carried out using a rigorous four-step procedure that results in one of four possible karst vulnerability ratings (low, moderate, high or very high).

4.6.1 Four-step Vulnerability Procedure

The four-step vulnerability assessment procedure, summarized in Figure 4.14, outlines a systematic method for determining a vulnerability rating for the total karst system within a karst polygon (considering three major criteria: epikarst sensitivity, the density of surface karst features and subsurface karst potential). The procedure also allows for the integration of three modifying factors: fine-textured, erodible soils; karst roughness; and unique or unusual karst flora/fauna sites. A vulnerability data form that can be used in the field to record data for karst polygons is provided in Appendix G (KFA Field Card #4).

Step I of the four-step procedure considers the level of *epikarst development* (see Section 4.4.2), derived from the frequency of vertical solutional openings versus their average depth to come up with a rating for epikarst development–low, moderate, high or very high.

Step II of the procedure integrates the epikarst development rating with the average soil thickness covering the epikarst to obtain a rating for *epikarst sensitivity*—low, moderate, high or very high. At this step, a modifier can be incorporated for the presence of fine-textured, erodible soils, which can increase the epikarst sensitivity rating by one category.

Step III integrates the rating for epikarst sensitivity with the density of surface karst features (see Section 4.4.3) to provide a rating for *surface karst sensitivity*—low, moderate, high or very high. A modifier for karst roughness can be incorporated at this step (see Section 4.4.4). If a high or very high level of karst roughness is evident, the surface karst sensitivity rating is raised by one category.

Step IV, the final step, adds the third dimension to the karst polygon by introducing a rating for *subsurface karst potential* (see Section 4.4.6), which is integrated with the rating obtained for surface karst sensitivity. This integrated rating represents the sensitivity of the *total karst system*, which is considered the *final karst vulnerability rating* for the polygon. A modifier for the presence of unique or unusual karst biota or favourable habitats can be incorporated at this step (see Section 4.4.7). If a unique or unusual habitat site for karst flora/fauna is present, the overall karst vulnerability rating is increased by one or possibly two categories.

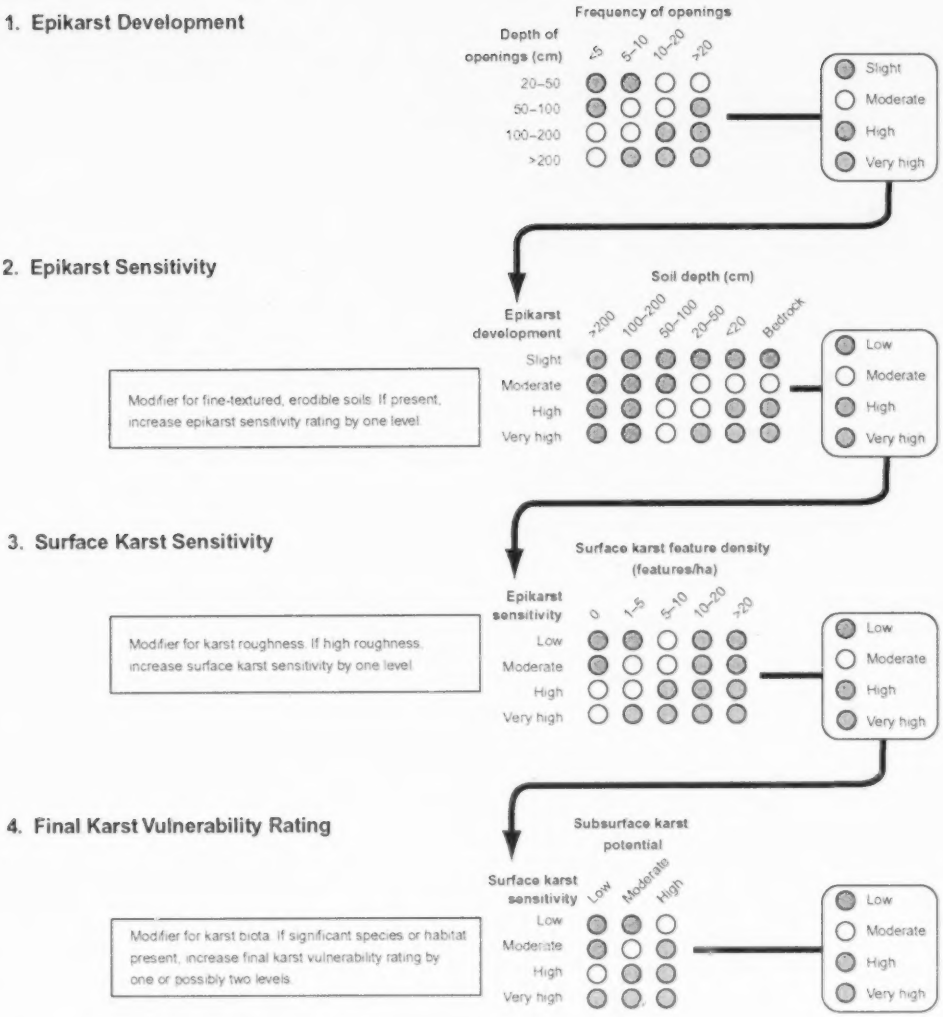

Figure 4.14. Four-step vulnerability assessment procedure.

4.7 Suggested Standards for the Karst Field Assessement Report and Map Compilation

The data from a KFA should be organized and presented spatially on a map, and the results outlined in an accompanying report. Map data can be produced in a format consistent with GIS or other digital systems. Manual maps are acceptable, but are of less use where integration into other data systems is required.

The base topographic map and the various layers developed during the office review should be modified and used to incorporate new inventory data, including:

- refinements to the boundaries of the karst unit and karst catchment;
- surface karst features (e.g., sinkholes, cave entrances) and epikarst zones;
- any mapped subsurface passages in plan view; and
- surface hydrological features (e.g., swallets, springs).

The karst polygon layer will display the polygon boundaries and their assigned vulnerability ratings and attribute categories (e.g., ratings for epikarst development and subsurface karst potential, ranges for surface karst feature distribution and any of the applicable modifiers—soil texture, karst roughness, or unique or unusual karst flora/fauna).

A KFA report should include the following essential elements:

- Objectives, scope, limitations and location of project.
- Who completed the work, for whom and when.
- Length of time in the field and weather conditions.
- Areas examined and areas not examined, with explanations.
- A list of information available and information used (e.g., maps, air photos, previous karst data).
- A description of anticipated development (e.g., harvesting methods, road construction techniques).
- A background description of the regional geological, geomorphological, hydrological and biophysical setting, including both topography and soil conditions.
- A description of field methodologies and procedures.
- A detailed description of the karst within and adjacent to the area of interest, including comments on the distribution and types of surface karst features, epikarst development, streams and hydrology, and subsurface karst potential. Data can be submitted in the form of narratives, tables or figures.
- Results of the vulnerability assessment procedure, with any limitations or concerns addressed.
- A discussion of the potential effects of the development within the karst area of interest, including comments on the possible consequences of these activities on significant surface or subsurface karst features.
- Conclusions and recommendations for management prescriptions or mitigative measures, including rationale.

Attachments or appendices to a KFA report should include:

- A regional location map (1:20 000 scale or greater).
- A 1:5000 or 1:10 000 scale map with topography, surface hydrology, karst feature distribution, likely subsurface hydrological connections, epikarst development and soil thickness.

- A 1:5000 or 1:10 000 scale map with rated vulnerability polygons, epikarst development ratings, surface karst features density ratings, subsurface karst potential ratings and any of the applicable modifiers.
- Three-dimensional schematics or drawings of the karst system in perspective view (emphasizing the types and extent of surface/subsurface linkages).
- References and glossary.
- Representative photographs or other visual records.

The report should be written in technically accurate language that is understandable to a wide range of readers, from management staff to field operators. It is suggested that procedures be developed to ensure sensitive karst inventory data (e.g., cave entrance locations) are kept secure. A secure/coded layer could be developed within a GIS system for cave locations to allow access to only specified personnel.

4.8 Karst Field Assessment Personnel Qualifications and Training

The following qualifications should be used as general guidelines for personnel completing KFAs. These qualifications will vary depending on whether personnel are responsible for coordinating, directing or performing the inventory work. Various combinations of training, experience and ability will have a bearing on qualification requirements.

Persons coordinating or directing field inventories should have an appropriate combination of post-secondary education and experience, and be well versed in karst processes. They should be familiar with designing inventory procedures, mapping techniques, carrying out karst field work, data analysis, and completing technical reports and maps. It is suggested that these people be registered professionals (e.g., RPF, PGeo, RPBio, PAg, PEng) who have successfully supervised a number of karst inventory projects in British Columbia or undergone karst inventory training.

Experienced forest technicians or engineers familiar with karst systems and processes can play an important role in the field work required to complete a KFA. With appropriate training, these people can perform the required field observations and measurements, and carry out the vulnerability assessment procedure.

In special cases, there may be a need to assemble a multi-disciplinary team for more detailed inventories of significant karst ecosystems encompassing multiple resources and values. Specialists for these kinds of inventories could include geomorphologists, hydrogeologists, biologists, paleontologists, archaeologists, etc., as required by the site-specific conditions. Experienced cavers or personnel familiar with safely working in the subsurface environment may be required for evaluating and mapping caves and other cavities. More knowledgeable and experienced speleologists would be required for the safe and efficient investigation of technically difficult and/or sensitive caves.

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6.0 Glossary

NOTE: Definitions for surface karst features are not provided in this glossary; those terms are defined in Appendix D.

Carbonate bedrock – rock consisting mainly of carbonate minerals, such as limestone or dolomite.

Catchment – the surface area drained by various sized watercourses.

Cave – a natural cavity in the earth that connects with the surface, contains a zone of total darkness and is large enough to admit a human. For the purposes of cave management, this term should also include any natural extensions, such as crevices, sinkholes, pits or any other openings, that contribute to the functioning of the cave system.

Conduit – a subsurface stream course filled completely with water and always under hydrostatic pressure.

Dolomite – a mineral composed of calcium magnesium carbonate. Rock chiefly composed of the mineral dolomite. Also called dolostone.

Dry valley – a valley that lacks a surface water channel.

Epikarst – the upper surface of karst, consisting of a network of intersecting fissures and cavities that collect and transport surface water and nutrients underground; epikarst depth can range from a few centimetres to tens of metres.

Geomorphic – pertaining to landforms and landscapes.

Gypsum – the mineral, hydrated calcium sulphate.

Interbed – a typically thin bed of rock material alternating with contrasting thicker beds.

Karren – channels or furrows separated by ridges resulting from solution on bedrock surfaces; the term is also used broadly to describe a variety of superficial solution forms on the surface of bedrock.

Karstification – action by water, mainly chemical but also mechanical, that produces features of a karst topography, including sinkholes, shafts and caves.

Limestone – a sedimentary rock consisting mainly of calcium carbonate.

Lithology – the physical characteristics and description of bedrock types.

Marble – timestone recrystallized and hardened by pressure and heat.

Physiographic – pertaining to the origin and evolution of landforms.

Slikensides – rock surfaces on either side of a fault plane which have been polished or marked by friction between the moving blocks.

Speleology – the study of caves and their environments.

Transect – a transverse line; a line that crosses from side to side.

Tufa – soft, porous calcium carbonate deposited in solution from springs or surface waters.

Windthrow – uprooting of trees by the wind.

Appendix A. Karst flora and fauna

Table A1. List of species and selected names of fauna associated with karst terrain, with a particular emphasis on British Columbia

NOTE: The intent of this list is not to cover all karst fauna, but rather to display examples of possible species, so as to illustrate the complexities of life that can exist in karst terrain both on the surface and subsurface.

Fauna	Names, description and general information
Bacteria	Typical examples occur within caves as 'moonmilk'—a calcareous deposit, orange iron and black manganese stains and rarer yellow sulphur deposits.
Fungi	Variety of mushrooms
Protista	—
Porifera and Bryozoa	Sponges rarely found
Turbellaria	Flatworms, numerous types found
Nematoda	—
Annelida	Segmented worms
Mollusca	Bivalvia and Gastropoda (freshwater shelled organisms)
Arachnida	Numerous types found. Harvestman spiders are common in many caves on Vancouver Island and the mainland.
Crustacea	
Amphipod	*Stygobromus quatsinensis*—found on Vancouver Island (Holsinger and Shaw, 1987). Also known on other coastal islands up to the Alaskan panhandle. *Stygobromus canadensis*—an amphipod from Castleguard Cave (Holsinger, 1981).
Symphyla and Chilopoda	Centipedes
Diplopoda	Millipedes
Insecta	Common in most caves, and includes Collembola (springtails), Diptera (flies, gnats) and Coleoptera (beetles). A greater diversity of butterflies and moths occur over limestone terrain, probably a function of increased plant diversity. One butterfly species, *Boloria natazhati*, in northern British Columbia is known to have a direct association with limestone.
Submariners	Any fauna associated with coastal caves or openings.
Amphibians	—
Fish	In British Columbia, salmon and/or trout have been observed in karst caves on Vancouver Island, Moresby Island and Princess Royal Island, but the nature of this association has not been scientifically investigated. However, there is documented evidence for an increase in productivity and population size of Coho salmon in karst terrain in southeast Alaska (Bryant et al., 1998).

Fauna	Names, description and general information
Birds	—
Mammals	
Bats	Karst/cave systems are used by bats, particularly for maternity and hibernating colonies. A red-listed species, *Myotis keenii,* is known to occur within the Weymer Creek Cave system on Vancouver Island (Chatwin et al., 1997). Additional bat species associated with karst in British Columbia include *M. lucifugus, M. thysanodes, Corynorninus townsendii* and *M. septentrionalis*. Nagorsen et al. (1993) lists all winter bat records for British Columbia in both caves and mines, some of which may be in karst.
Other mammals	Karst and its associated surface or near-surface features (particularly on the north of Vancouver Island) may also provide habitat for a number of other mammals, such as deer, weasels, martens and shrews.

Table A2. List of species and selected names of flora associated with karst terrain, with a particular emphasis on British Columbia

NOTE: The intent of this list is not to cover all karst flora, but rather to display examples of possible species, so as to illustrate the complexities of life that can exist in karst terrain.

Flora	Description
Trees	No types known to be specifically associated with limestone bedrock.
Shrubs	No types known to be specifically associated with limestone bedrock.
Wildflowers	
Epipactis gigantea	A red-listed orchid found around calcium-rich seeps (e.g., Pilot Peninsula, Kootenay Lake).
Grasses	No types known to be specifically associated with limestone bedrock.
Ferns	
Asplenium virde (green spleenwort)	Calciphile found on moist and shaded vertical bedrock faces or crevices, middle to alpine elevations (Pojar and MacKinnon, 1994).
Asplenium adulterinum	A blue-listed fern found on central Vancouver Island (Clayquot Plateau and Tahsis Mountain) and in the Pierce Range. Habitat is on dry to mesic walls of limestone fissures in subalpine zones (Douglas, 1998).
Hedysarum occidentale	Occasionally found on karst, such as Marble Meadows, Vancouver Island (Douglas, 1998).
Bryophytes (Mosses and Liverworts)	
Hypopterygium fauriei	See Scofield, 1992.
Fissidens limbatus	See Scofield, 1992.
Preissia quadrata	See Scofield, 1992.
Lichens	See Vitt et al., 1988.
Aquatics	—

Table A3. List of possible contacts for karst flora and fauna in British Columbia

NOTE: This list is not intended to be comprehensive, but rather as a starting point for karst inventory workers. Personnel, phone numbers and e-mails will likely change over time. Stokes (1996) also provides additional karst flora/fauna contacts outside of British Columbia.

Specialist name	Association	Field of karst flora/ fauna interest	Contact numbers
Trudy Chatwin Rare and Endangered Species Specialist	BC Ministry of Environment, Lands and Parks, Nanaimo	Bats	(250) 751-3150 tchatwin@nanaimo.env.gov.bc.ca
Hans Roemer	BC Parks, Victoria	Plants	(250) 387-4649
Dave Nagorsen Curator, Mammalogy	Royal British Columbia Museum, Victoria	Paleontology of mammals. Bones.	(250) 387-2933
Crispin Guppy Forest Ecosystem Specialist	BC Ministry of Environment, Lands and Parks, Quensel	Moths and Butterflies	(250) 992-4490
Laura Friis Small Mammal and Herpetofauna Specialist	BC Ministry of Environment, Lands and Parks, Victoria	Bats and Mammals	(250) 387-9755 laura.friis@gems8.gov.bc.ca
Syd Canning Program Zoologist	BC Ministry of Environment, Lands and Parks, CDC, Victoria	Fauna	(250) 387-8242 Syd.Cannings@gems9.gov.bc.ca
George Douglas Program Botanist	BC Ministry of Environment, Lands and Parks, CDC, Victoria	Flora	(250) 356-9554 George.Douglas@gems7.gov.bc.ca
Adolf Ceska Community Ecologist	BC Ministry of Environment, Lands and Parks, CDC, Victoria	Flora	(250) 356-7855 Adolf.Ceska@gems4.gov.bc.ca
Marta Donnovan Biological Information Coordinator	BC Ministry of Environment, Lands and Parks, CDC, Victoria	Flora and Fauna	(250) 356-0928 elpcdcdata@victoria1.gov.bc.ca
Salman Rasheed Wildlife Biologist	BC Ministry of Environment, Lands and Parks, Campbell River	Mammals	Sal.Rasheed@gems1.gov.bc.ca

Appendix B. Karst and related attributes requiring identification, location and measurement during the planning-level inventory and the karst field assessment

NOTE: Not all of these attributes need to be examined extensively; the list simply illustrates which attributes should be considered during the inventory work. More emphasis, detail and accuracy in recording attributes is required at the KFA level compared to the planning level.

Karst attribute	Planning-level inventory and KFA data collection requirements
Bedrock Geology	
Karst lithology	Type (e.g., limestone, dolomite, gypsum). Form (e.g., massive, interbedded) and proportion. *(See Table 3.2)*
Other lithology	Types (e.g., volcanics, intrusives) and contact relationship (e.g., faulted, intrusive, gradational).
Karst unit boundary	Where possible, located to nearest 25 m at the planning level and 10 m at the KFA level. Mapped using standard line notation for defined, approximate and assumed.
Extent of bedrock exposure	Mapped using standard conventions (e.g., dotted line or 'x' for small).
Bedding planes	Dip and strike measured by compass using standard geological procedures (Right Hand Rule).
Major faults	Dimensions and description. Strike/dip of fault plane, offset direction, slikensides.
Major folds	Size. Orientation of fold axis and axial plane. Type (e.g., anticline or syncline).
Minor faults	Dimensions and description. Strike/dip of fault plane, offset direction, slikensides.
Minor folds	Size. Orientation of fold axis and axial plane. Sense of movement.
Joint sets	Orientation, spacing and openness.
Slope Geomorphology and Surficial Materials	
Slope gradient class	Measure gradient in percent. See *Terrain Classification System for British Columbia.*
Slope topography	Slope position (e.g., mid, upper or lower slopes), form (e.g., uniform, concave, irregular, straight).
Karst micro-topography	Local small-scale topography reflecting karst processes *(See Table 3.3)*
Surficial type and materials	Type (e.g., moraine, fluvial, colluvium), texture (e.g., silty or sandy) thickness (e.g., thin veneer <0.2 m, veneer <1 m, blanket >1 m, or mantle), weathering depth. See *Terrain Classification System for British Columbia.*
Slope drainage	Rapidly, well, moderately well, poorly or very poorly drained. See *Terrain Classification System for British Columbia.*
Forest floor/organic layer	Type, texture and depth. See *Terrain Classification System for British Columbia.*

Karst attribute	Planning-level inventory and KFA data collection requirements
Surface Karst Features – See Appendix D and Figure 4.7 for details.	
Karst Hydrological Features – See Appendix D and Figure 4.7 for details.	
Geomorphic Hazards and Natural Disturbances	
Fire/burn areas	Extent and intensity.
Tree windthrow	Orientation, age, extent and species.
Landslides	Location, size and materials.
Rockfall and soil slumps	Location, size and materials.
Gully sidewall and channel erosion	Location, size and materials.
Surface flooding	Level, size and frequency.
Karst Flora and Fauna - See Appendix A and Table 3.8.	
Unusual plants or plant communities	Species, location and extent.
Unusual fauna or evidence of fauna	Species, location and extent.
Favourable flora habitat	Location and extent.
Favourable fauna habitat	Location and extent.
Karst Air – See Appendix C.	
Slope aspect	Azimuth.
Drafting around cave entrances	Amount and direction.
Air temperature around surface karst depressions, openings and cave entrances	Estimates of maximum, minimum and mean.

Appendix C. Procedure for determining surface karst feature significance

Introduction

The procedures outlined here are largely based on *Classification System for Discrete Mesoscale and Microscale Surface Karst Features* (Griffiths, 1993). Significant surface karst features are critical components of the karst system that can be negatively impacted by development activities (e.g., forest harvesting or road construction). These impacts can, in many cases, be transmitted to other parts of the karst system (e.g., the movement of logging debris from a sink point into cave passages).

Significant surface karst features can include sinkholes, shafts, grikes, swallets, bluffs, canyons, springs, cave entrances. Determining the significance of surface karst features requires a qualitative evaluation of a number of criteria. These criteria include: dimensional characteristics; connectivity; hydrology; geological values; biological values; scientific and educational values; archaeological, cultural and historical values; recreational and commercial values; rarity and abundance; and visual quality (see Figure C1). Many of these criteria are interrelated and dependent on each other. For example, a dimensionally large swallet would provide a good hydrologic connection to the subsurface, as well as have strong visual appeal.

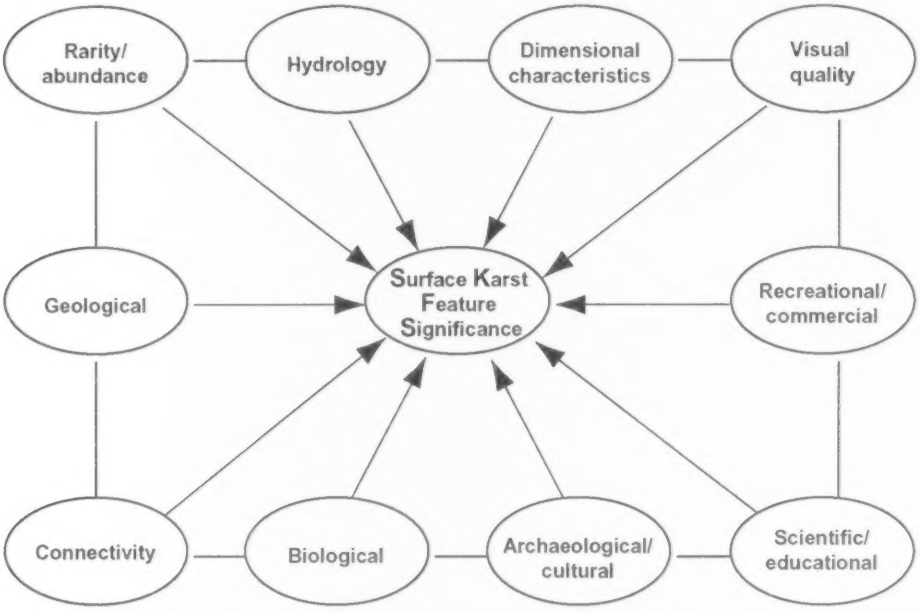


Figure C1. Characteristics and values contributing to surface karst feature significance.

Significance Criteria

Dimensional Characteristics

The dimensional characteristics of surface karst features are the width, length and depth measurements commonly taken during a karst field assessment. As a general rule, the greater the dimensions, the greater the significance; however, this criteria can be strongly tempered by rarity. For example, a 20 m diameter by 15 m deep sinkhole that is common in one location would likely not be as significant as the same sized sinkhole that is rare in another location. (Note: Calculating the relative volumes between sinkholes of different shapes and dimensions can be an effective way of comparing them; see Figure D4 in Appendix D). Table C2 indicates some of the dimensional characteristics to consider for various types of surface karst features.

Connectivity

The degree of connectivity or openness between a surface karst feature and other surface karst features or the subsurface contributes to the significance of the feature. This connectivity can be through air-filled or water-filled pathways. The presence of water flow, either disappearing or emerging, is an indication of the connectivity within the system. Air flow can be identified by obvious 'drafting' in or out of a surface opening; however, in many cases, an air-filled connection is difficult to confirm, especially for small cavities. As a general rule, the greater the connectivity between a surface karst feature and the rest of the karst system, the greater the significance of the feature.

Hydrology

The size of karst lakes and ponds is the principal factor in determining their significance; in general, the larger they are, the more significant they are. Determining the significance of swallets and springs is somewhat more complex. The size of the catchment area for a sinking stream needs to be considered when determining the significance of a swallet. Swallets fed by intermittent or ephemeral sinking streams may be less significant than those fed by permanent sinking streams. Swallets fed by permanent sinking streams with relatively large catchments (e.g., greater than 100 ha) are generally most significant. Springs known to contribute to productive surface streams (i.e., rising streams) or domestic water supplies are significant.

Geological Value

The host bedrock for surface karst features can have a bearing on significance. For example, if a surface karst feature occurs in a bedrock unit or type that is uncommon or rare, it is likely to be significant. Alternatively, the presence of a surface karst feature within a bedrock unit that does not commonly contain karst features may also be significant.

Biological Value

The evaluation of biological values primarily considers the presence of fish in karst waters, and unique or unusual karst-specific flora and fauna and/or their associated habitats. Any fish found in karst waters (lakes, ponds, streams) would increase the significance of the feature. In many cases, large surface karst features (e.g., a large sinkhole) are likely to be suitable habitats for karst-specific flora and fauna. A specialist may be required to identify the specific species of karst flora or fauna; however, an experienced karst field worker should be able to determine the presence of unusual biota or habitats. Section 4.4.7 details some of the likely habitats suitable for karst-specific flora and fauna, and cites available resources for assistance

in identifying or confirming species (see Table 3.8). Confirmation of karst-specific flora or fauna associated with a surface karst feature would increase its significance.

Scientific and Educational Values

Scientific and educational values associated with surface karst features are broad in scope and relatively complex to evaluate. Large surface karst features and those with connections to the subsurface can provide important scientific and educational opportunities in the fields of geology, biology, paleontology, climate change, and landform evolution. Obvious signs of scientific or educational values would increase the significance of a surface karst feature.

Archaeological, Cultural and Historical Values

Complete evaluation for archaeological, cultural or historical values associated with surface karst features requires specialized knowledge and expertise, and may include archival research and/or archaeological investigation. It may also include consultation with local First Nations groups and the BC Heritage Conservation Branch. Karst field workers should be aware of the likely conditions where these values might occur (e.g., shoreline caves, rock shelters, springs, prominent cave entrances, etc.). Evidence of past human use of surface karst features (e.g., wall paintings or fire pits) is an obvious indicator of archaeological value, and would lead to a higher significance rating.

Recreational and Commercial Values

The determination of recreational values for caves requires a separate evaluation, as detailed in the *Cave/Karst Management Handbook for the Vancouver Region* (BC Ministry of Forests, 1994). However, an experienced karst field worker should be able to determine the potential recreational value for surface karst features based on attributes such as attractiveness, access, interest value, uniqueness, hazard potential, etc. Commercial values that could be considered include commercial surface karst viewing and caving opportunities, or the potential of a spring for commercial mineral water production. Surface karst features with recreational or commercial potential would receive a higher rating for significance.

Rarity and Abundance

The apparent rarity or abundance of a surface karst feature can greatly influence its relative significance. Rarity and abundance can be considered at a variety of scales from local, regional and provincial to national and international. It can also be considered with respect to other values (e.g., geological, biological, scientific). For example, the presence of a surface karst feature within a karst ecosystem that is poorly represented elsewhere would increase its significance. In general, rare surface karst features would be considered more significant than abundant ones.

Visual Quality

The visual quality of surface karst features has the potential to contribute to both recreational and commercial appeal. The association of a surface karst feature with flowing water, particularly within attractive natural settings (e.g., temperate rain forest), can increase the significance of the feature.

Procedure for Determining Significance

The procedure for determining the significance of a surface karst feature is a qualitative system using three categories of significance potential (low, moderate or high). These three categories are in turn used to determine whether a feature is 'significant' or 'non-significant' (see Table C1).

The decision to apply the significance procedure on a surface karst feature is primarily based on experience and the guidelines provided in Table C2. In some cases, additional data collection and measurements of potentially significant surface karst features may be required.

Table C1 provides a list of the significance criteria to be evaluated and three categories for significance potential—low, moderate or high (L, M or H). Each of the significance criteria is evaluated, if applicable. Once all the significance criteria have been evaluated, an overall significance determination is made based on the generalized rules at the bottom of the table.

A tabulated field card to assist in determining the significance of surface karst features is provided in Appendix G (Field Card #3).

Table C1. Matrix table for evaluating the significance of surface karst features

Significance Criteria	Significance Potential			Unknown	Not Available	Comments
	Low	Mod.	High			
Dimensional Characteristics						
Connectivity						
Hydrology						
Geological						
Biological						
Scientific/Educational						
Archaeological/ Cultural						
Recreational/ Commercial						
Rarity/Abundance						
Visual Quality						

Generalized rules for determining whether a feature is significant or non-significant:

1. If any of the significance criteria is high, the feature is significant.
2. If any two significance criteria are moderate, the feature is significant.
3. If one significance criteria is moderate and one or more criteria are unknown, the feature is significant.
4. If none of the above, the feature is probably not significant.

Table C2. Guidelines for evaluating significance criteria of selected surface karst features

Surface karst feature type	Factors to be considered in evaluating significance
Bluffs and canyons	For karst bluffs and canyons, aspect and dimensions are likely to be important, particularly height, which could influence visual quality. A critical factor would be seepage, as this could provide habitat for certain karst flora and fauna.
Hummocks/Knolls	Dimensions for these type of positive relief features could be important, particularly if the feature is prominent in the surrounding landscape. However, both scale and rarity would need to be taken into consideration. Visual quality could have an influence.
Sinkholes	The larger the dimensions of a sinkhole, the greater the likelihood of significance; however, this needs to be tempered with rarity. A large (e.g., >20 m diameter) sinkhole could also have its own microclimate, resulting in habitat for unique or unusual karst flora. The openness of a sinkhole at its base would be another important consideration.
Grikes and epikarst zones	The areal and depth dimensions of grikes or epikarst zones are an important consideration for significance. Deep (e.g., >4 m) and/or open-bottomed features could also influence the connectivity to the subsurface and provide habitat for karst flora and fauna.
Swallets and springs	For the most part, dimensionally large swallets, and springs with permanent flow, are likely to be significant. However, smaller swallets and springs could also be significant, as they are evidence for connectivity within the karst system. In many cases, springs and swallets have their own microclimate, providing potential habitat for karst flora and fauna.
Cave entrances and rock shelters	Dimensionally large cave entrances and rock shelters are likely to be significant as they could potentially provide habitat for karst flora and fauna. The likelihood for other values (e.g., archaeological, cultural) is also likely to be greater. However, small cave entrances should not necessarily be considered non-significant, as they can lead to large cave systems.

Appendix D. Classification of surface karst features

Surface karst features are those features of the karst landscape that can be viewed by an observer on the ground up to the threshold of daylight in subsurface openings, including cave entrances. Subsurface karst features are those that are beyond the threshold of daylight.

Surface karst features can be subdivided into the following broad categories:

- insurgences;
- karst springs – resurgences and exsurgences;
- linear features; and
- intersection features.

Insurgences

Insurgences are features that introduce surface water to the subsurface karst environment. The term is independent of size and volume, and describes no specific morphological feature. Insurgences can be characterized as being hydrologically perennial or intermittent based on the hydrological process that takes place. The morphology of an insurgence depends on the structure and lithology of the soluble bedrock present, the local relief, and the volume of water sinking underground.

Confluent Insurgences or Swallets

A *confluent insurgence* or *swallet* is a type of insurgence with a concentrated water flow, and implies existence of a subsurface conduit. The surface water enters the subsurface after it has been concentrated into identifiable streams. The water will usually sink at separate locations that can be seen and measured as point inputs. Swallet formation is dependent on the presence of impervious rock formations or thick overburden, which provides a surface on which meteoric water can collect as surface streams. For inventory purposes, a swallet may also refer to a concentrated water loss in a streambed even though there is no marked depression. A swallet refers to the site of the water loss, not the stream that leads to it.

In many cases, the growth and evolution of a subsurface conduit system results in the abandonment of some swallets in favour of new upstream swallets called progressive swallets. The adjective abandoned is applied to describe the older inactive insurgence. Swallets that are only utilized when upstream insurgences cannot handle peak water flows are termed overflow swallets.

Swallets frequently occur in clusters or complexes associated with the course of pre-existing subsurface conduits. This is because the underlying conduits serve as a drain for surface water. Swallets can also cluster if one of the insurgences cannot accommodate peak flows, resulting in the use of overflow swallets. In mantled karst units, swallets tend to cluster where the soluble rock is exposed, as this is where surface water flow is more likely to sink.

Diffuse Insurgences

A *diffuse insurgence* is where surface water enters the soluble bedrock as a series of small, dispersed inputs by percolation (through overburden, if it exists) into small openings in the bedrock. In this case, water flow is not related to a definable surface stream. The infiltration routes are small openings, usually joints or fractures in the bedrock. The concentration of water flow takes place in the subsurface environment, not the surface environment as with confluent insurgences or swallets.

Karst Springs

Karst springs are features that discharge water from the subsurface environment, and can be classified as either resurgences or exsurgences.

Resurgences

Resurgences are where water collected at swallets is transmitted by solution conduits and discharged to the surface environment to form a surface stream (i.e., *rising stream*). These features are the downstream end members of karst networks. The actual surface opening may be totally or partially obstructed by collapse or unconsolidated surficial materials, including colluvium. The observable openings can be perennially or intermittently submerged (i.e., flooded). *Overflow springs* are resurgences that are used when the normal spring is incapable of handling the volume of water transmitted to it. As with insurgences, the maturation of a karst unit may result in the abandonment of resurgences in favor of newer ones. In such a case, the old discharge point is classified as an *abandoned karst spring*.

Exsurgences

Exsurgences are the downstream reappearance of local infiltration (i.e., a diffuse insurgence) of surface water. The term is applied if the origin of the discharge water cannot be confirmed to be predominantly a confluent insurgence or a swallet.

Linear Features

The majority of linear features can be divided into two broad types: fluviokarst and merokarst. *Fluviokarst* features are found in karst landscapes in which there is evidence of past or present fluvial activity. *Merokarst* features are found in areas of imperfect karst topography, where surface drainage and dry valleys are found in addition to some karstic features.

Examples of fluviokarst features:

A *sinking stream* is a small stream that disappears underground at a karst insurgence, usually a swallet.

A *losing stream* is a surface watercourse that gradually loses water along its bed, particularly when unconsolidated sediments form the bed.

A *gaining stream* is a surface stream in karst that gradually gains water along its bed.

An *interrupted stream* is one that repeatedly disappears and resurges.

A *rising stream* is the surface course of an emergent underground stream. A karst river is a more important watercourse that originates from a karst spring.

Examples of merokarst features:

A *dry drainage segment* is the portion of an elongate natural karst depression between intersecting depressions or other terminations.

A *karst canyon* is a deep and narrow gorge or ravine, with vertical or subvertical slopes underlain by soluble rock containing a perennial or intermittent stream. This feature in karst is frequently formed by a river originating from impervious rock outside the karst unit. A *slot canyon* is a soluble bedrock canyon with vertical or overhanging walls and a depth-to-width ratio greater than 3:1.

A *swale* is a slightly elongate natural depression in generally level karst terrain, without a permanent watercourse. It is generally shallower than a draw or ravine. The gradient of the sideslopes is generally less than 20%.

A *draw* or *ravine* is an elongate depression in sloping karst terrain, without a permanent watercourse. The gradient of the sideslopes is generally between 20 and 40%.

A *dry gully* has steeper sides than a draw and is usually found in steeper karst terrain. The gradient of the sideslopes is generally greater than 40%.

A *karst valley* is an elongate solution valley with inclined sides. The valley may or may not contain a stream. A *blind karst valley* is a valley that usually terminates at a swallet. It may have a perennial or intermittent stream that sinks at its lower end, or it may be a dry valley. A *half-blind karst valley* is a blind valley that overflows to a surface stream when the flow of water entering the blind valley exceeds the maximum capacity that the downstream swallet can accept.

Surface karst features that form abrupt slopes on one side, such as escarpments and cliffs, are termed linear *karst declivities*. For inventory purposes, these features must have an altitudinal difference of at least two meters, and have a length greater than 10 meters.

Examples of linear karst declivities:

A *karst steephead* is the head of a valley in a karst unit, generally short and restricted at the headward end by an escarpment. It is commonly associated with a karst spring.

A *solution scarp* is a long, cliff-like ridge of soluble bedrock, a steep slope, or drop of a precipitous line of cliffs, terminating high land abruptly. They can be formed by the more active solution of the lower area or by corrosional undercutting of the base.

A *cliff* is a high, steep face of soluble bedrock.

A *cuesta* is a long, low ridge with a relatively steep face, or escarpment on one side and a long, gentle slope on the other.

Intersection Features

Intersection features are the connections that exist between the surface and subsurface karst environments, and do not relate to an appreciable water insurgence to, or emergence from, a known subsurface conduit system. Weathering phenomena other than solution process can contribute to their formation. After initial formation, an intersection feature may be transformed into an insurgence (or resurgence) by the capture (or release) of water from nearby areas.

Negative Relief Point Features

Negative relief point features are the most common type of intersection features. These may appear to be solutional in origin, but their final surface expression may be due to other weathering processes.

Examples of negative relief point features:

A *solution pan* is a shallow dish-shaped depression in soluble bedrock, with a flat bottom and steep, occasionally overhanging sides. The diameter of these features ranges from several decimeters to several meters. For inventory purposes, a solution pan has a depth greater than 20 cm and a diameter ranging from 20 cm to two meters maximum. The width-to-depth ratio is two, minimum.

A *sinkhole* is a topographically closed karst depression, wider at the rim than it is deep. It is commonly of a circular or elliptical shape with a flat or funnel-shaped bottom. A sinkhole can have sinuous interior contours, but no angular contours. For inventory purposes, a sinkhole must have a deepest point at least two meters below the surrounding landscape, and have a width greater than two meters. A *shakehole* is a variant of a sinkhole, and is formed by solution, subsidence or compaction in loose drift or alluvium overlying beds of limestone. An *uvala* is a large karst depression with a rugged bottom, often formed by coalescent sinkholes. It may contain other smaller nested features. For example, the host uvala may contain a karst stream that eventually sinks at a swallet.

A *shaft* is a deep solution hole, generally circular in outline, having vertical or nearly vertical walls. It tends toward a cylindrical shape, and is without a passage or chamber leading from it. A shaft is a vertical cavity with approximately equal horizontal dimensions and a much larger vertical dimension. Also referred to as a pothole, it is wider than a chimney.

A *karst pond* is a karst depression enclosing a standing water body. For inventory purposes, it has a diameter less than 10 meters and a depth less than one meter. A karst depression enclosing a standing water body with a diameter greater than 10 meters, and with a depth greater than one meter, is termed a *karst lake*. A *karst fen* is a marshy depression developed in sinkhole terrain. A *karst window* is a depression revealing part of an underground stream flowing across its floor (also an unroofed part of a cave).

A *natural well* is a large sinkhole with subvertical walls, containing a water body that intersects the phreatic zone.

Examples of vertical intersection features, subject to certain size limits, used for estimating epikarst development (see Section 4.4.2):

A *karst joint* is a fracture in soluble bedrock, generally more or less vertical or transverse to bedding, along which no appreciable movement has occurred. For inventory purposes, joints must have a width less than 20 cm, and an elongation ratio of 1.5, maximum. They are generally smaller than a fissure, but larger than a rock fracture that is not enlarged by solutional weathering. The depth-to-width ratio is two, minimum. A *karst fissure* is an open crack in bedrock that is only slightly enlarged by solution weathering. For inventory purposes, fissures must have a width of between 10 and 20 cm, and an elongation ratio of 1.5, maximum. They are generally larger than a joint, but smaller than a grike. The depth-to-width ratio is two, minimum.

A *grike* is a deep, narrow, vertical or steeply inclined, rectilinear slot with almost parallel sides. Grikes are usually found in a bedrock outcrop and are caused by solution along a joint. For inventory purposes, they have a depth greater than 20 cm and a diameter ranging from 20 cm to two meters. The elongation ratio is two, minimum.

For inventory purposes, a *karst cleft* is a rectilinear hole with the form of a large fissure or grike, between two abrupt walls at least 20 cm apart. The maximum width is less than two meters. The elongation ratio is two, minimum. The depth-to-width ratio is also two, minimum.

A *solution* tube is a rounded solution hole or small tunnel of any orientation. The vertical forms, called chimneys, are generally larger and more rounded than a grike. For inventory purposes, a tube is a vertical or subvertical cylindrical hole with a diameter of greater than 50 cm but less than two meters, extending from the surface to a depth of a two meters or more. The elongation ratio is two, minimum. The depth-to-width ratio is also two, minimum. A *pipe* is a vertical or subvertical cylindrical hole with a diameter of less than 50 cm, extending from the surface to a depth of one meter or more. For inventory purposes, the elongation ratio is 1.5, maximum. Pipes are often filled with soil and unconsolidated sediments and/or breccia. The depth-to-width ratio is two, minimum. A *chimney* is a solution hole, generally circular in outline, having a marked degree of sinuosity. The feature is without a passage or chamber leading from it. It has approximately equal horizontal dimensions at the surface opening and a much larger vertical dimension. It is generally smaller in cross-sectional area than a shaft.

Lateral Intersection Features

Lateral intersection features frequently occur along retreating cliffs, and where steep slopes uncover pre-existing solution conduits.

Examples of lateral intersection features:

A *natural arch* is a small natural rock bridge that does not span a karst valley.

A *natural bridge* is a large natural rock bridge that crosses a karst valley.

A *natural tunnel* is a horizontal or sub-horizontal cavity open at both ends, generally fairly straight in direction, and fairly uniform in cross section. No part of the feature is beyond daylight.

Positive Relief Features

A positive relief feature is a residual landform that rises above the surrounding karst landscape.

Examples of positive relief features:

A convex *outcrop* is a small exposure of soluble bedrock projecting through overlying layers of detritus and soil.

A *hum* is a small residual hill of soluble rock standing above a recently eroded soluble rock surface. For inventory purposes, a karst hum must rise at least two meters above the surrounding landscape and have a basal area of not less than 0.01 ha, but less than 0.1 ha. A *hummock* is a knoll or small elevation, larger than a hum. For inventory purposes, it has a basal area greater than 0.1 ha.

A *karst ridge* is a long, narrow hill of soluble bedrock. For inventory purposes, a karst ridge is a positive landform rising at least two meters above the surrounding landscape, is more than 10 m long (as measured along the longitudinal axis), and has a minimum 4:1 length-to-width ratio.

Cave Entrances

Surface openings large enough to admit a human being, connecting to interior cavities that contain a zone of complete darkness, are *cave entrances*. A cave entrance is part of the cave or cave system and may be nested within one or more other surface karst features. For example, a cave entrance may be located within a sinkhole and swallet—these are also examples of nested or compound karst features.

A cursory inspection of the cave entrance can be made to establish if penetrable interior cavities exist beyond the threshold of daylight. If a subsurface inspection is deferred for any reason, the feature is tentatively classified as a *possible cave entrance*. Cave entrances can vary widely with scale and structure. They are categorized according to whether they are dimensionally *large* or *small*, or have *vertical* or *horizontal* aspects. Large entrances have a cross-sectional area greater than 10 m^2. Small cave entrances have a cross-sectional area less than 10 m^2 but are penetrable (without removing obstructions or excavation).

For inventory purposes, the cross-sectional area of a horizontal or sub-horizontal cave entrance is visually estimated at the vertical plane formed by the most probable *dripline*. The dripline is a line on the ground at a cave entrance formed by drips from the rock above. The cross-sectional area of a vertical or subvertical entrance (e.g., a shaft or grike) is visually measured at the horizontal plane formed by the highest closed contour.

Miscellaneous Surface Karst Features

A *rock shelter* is a solution hollow with a more or less level floor reaching only a short way into a hillside or under a fallen block. No enterable part of the feature is beyond the reach of daylight.

Figure D1 provides mapping elements and symbols, and measurement standards for surface karst features.

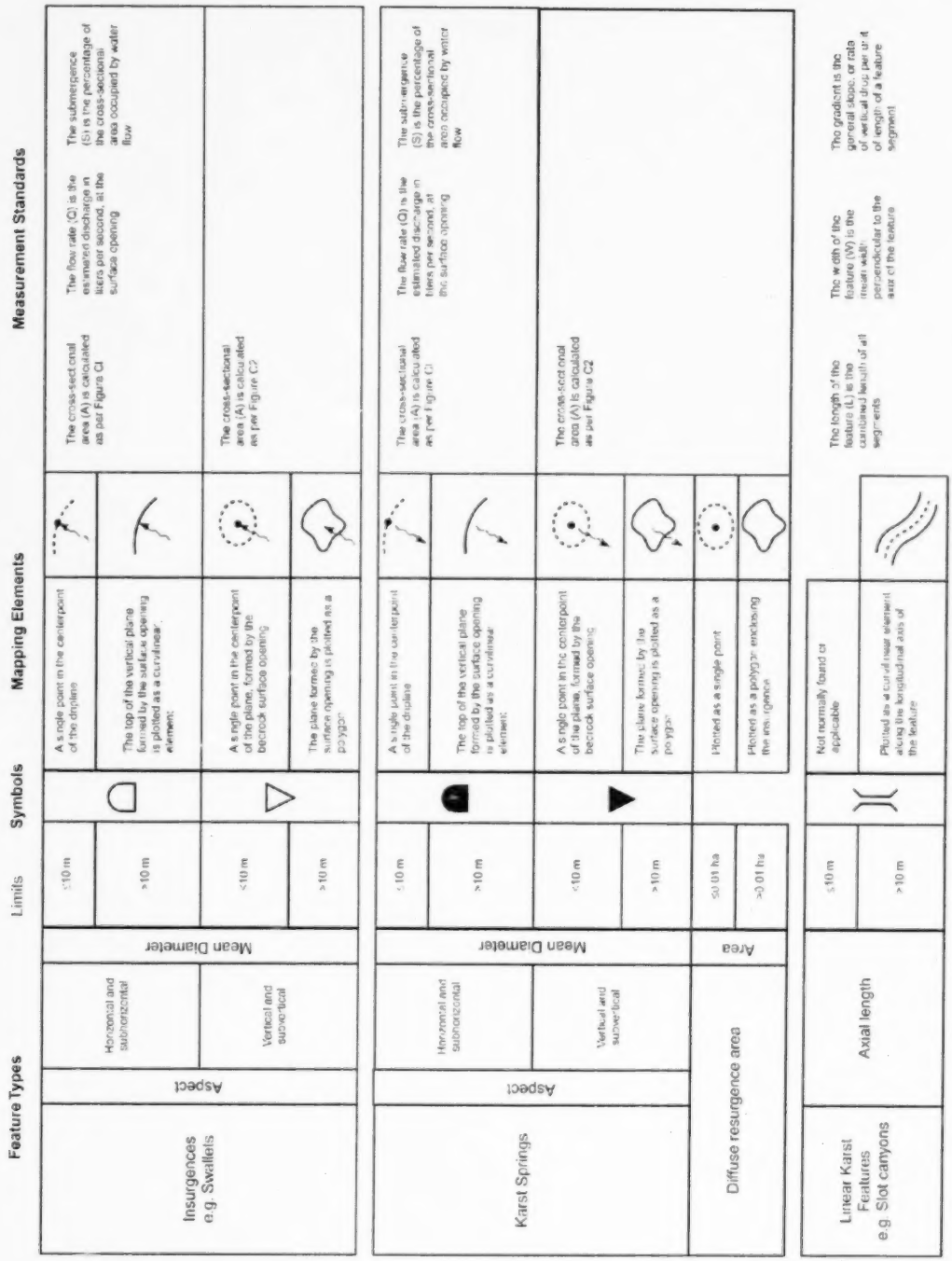

Feature Types
Limits
Symbols
Mapping Elements
Measurement Standards
Insurgences e.g. Swallets
Aspect
Horizontal and subhorizontal
Vertical and subvertical
Mean Diameter
<10 m
>10 m
<10 m
>10 m
A single point in the centerpoint of the dolline
The top of the vertical plane formed by the surface opening is plotted as a curvilinear element
A single point in the centerpoint of the plane, formed by the bedrock surface opening
The plane formed by the surface opening is plotted as a polygon
The cross-sectional area (A) is calculated as per Figure C1
The flow rate (Q) is the estimated discharge in liters per second, at the surface opening
The submergence (S) is the percentage of the cross-sectional area occupied by water flow
The cross-sectional area (A) is calculated as per Figure C2
Karst Springs
Aspect
Horizontal and subhorizontal
Vertical and subvertical
Mean Diameter
<10 m
>10 m
<10 m
>10 m
A single point in the centerpoint of the dolline
The top of the vertical plane formed by the surface opening is plotted as a curvilinear element
A single point in the centerpoint of the plane, formed by the bedrock surface opening
The plane formed by the surface opening is plotted as a polygon
The cross-sectional area (A) is calculated as per Figure C1
The flow rate (Q) is the estimated discharge in liters per second, at the surface opening
The submergence (S) is the percentage of the cross-sectional area occupied by water flow
The cross-sectional area (A) is calculated as per Figure C2
Diffuse resurgence area
Area
≤0.01 ha
>0.01 ha
Plotted as a single point
Plotted as a polygon enclosing the resurgence
Linear Karst Features e.g. Slot canyons
Axial length
≤10 m
>10 m
Not normally found or applicable
Plotted as a curvilinear element along the longitudinal axis of the feature
The length of the feature (L) is the combined length of all segments
The width of the feature (W) is the mean width perpendicular to the axis of the feature
The gradient is the general slope, or rate of vertical drop per unit of length of a feature segment

Figure D1. Mapping elements and symbols, and measurement standards for surface karst features.

Feature Types		Limits	Symbols	Mapping Elements		Measurement Standards
Linear Declivities e.g. Cliffs	Altitudinal Difference	2 m ≤ h ≤ 10 m		Plotted as a single point in the centerpoint of the landform		The mean diameter of the feature (D) is the average length of two right angle lines crossing the maximum length (L) and width (W) relative to the area of exposed bedrock The height of the feature (H) is the maximum height of the feature relative to the mean elevation of the base of the feature
		>10 m		The orpline is used and plotted as a curvilinear element		
Negative Relief Point Features e.g. Sinkholes	Mean Diameter	<10 m		A single point in the centerpoint of the plane formed by the bedrock surface opening		The cross-sectional area (A) is calculated as per Figure C3 The volume (V) is calculated as per Figure C3
		>10 m		The plane formed by the surface opening is plotted as a polygon		
Cluster of small features	Area	≤0.01 ha		Plotted as a single point		
		>0.01 ha		Plotted as a polygon enclosing the insurgences		
Lateral Intersection Features e.g. Natural arches and bridges	Axial length	≤10 m		Plotted as a single point in the integrated centerpoint of the span		The span length (L) is the axial length of rock suspended over the enclosed air space The span width (W) is the width of the rock at its centerpoint
		>10 m		The span is plotted as a line		
Natural tunnels		≤10 m		Plotted as a single point		The length of the tunnel (L) is the maximum distance between the orpline centerpoints of the surface openings
		>10 m		Tunnel openings are plotted as separate points		

Figure D1. Continued.

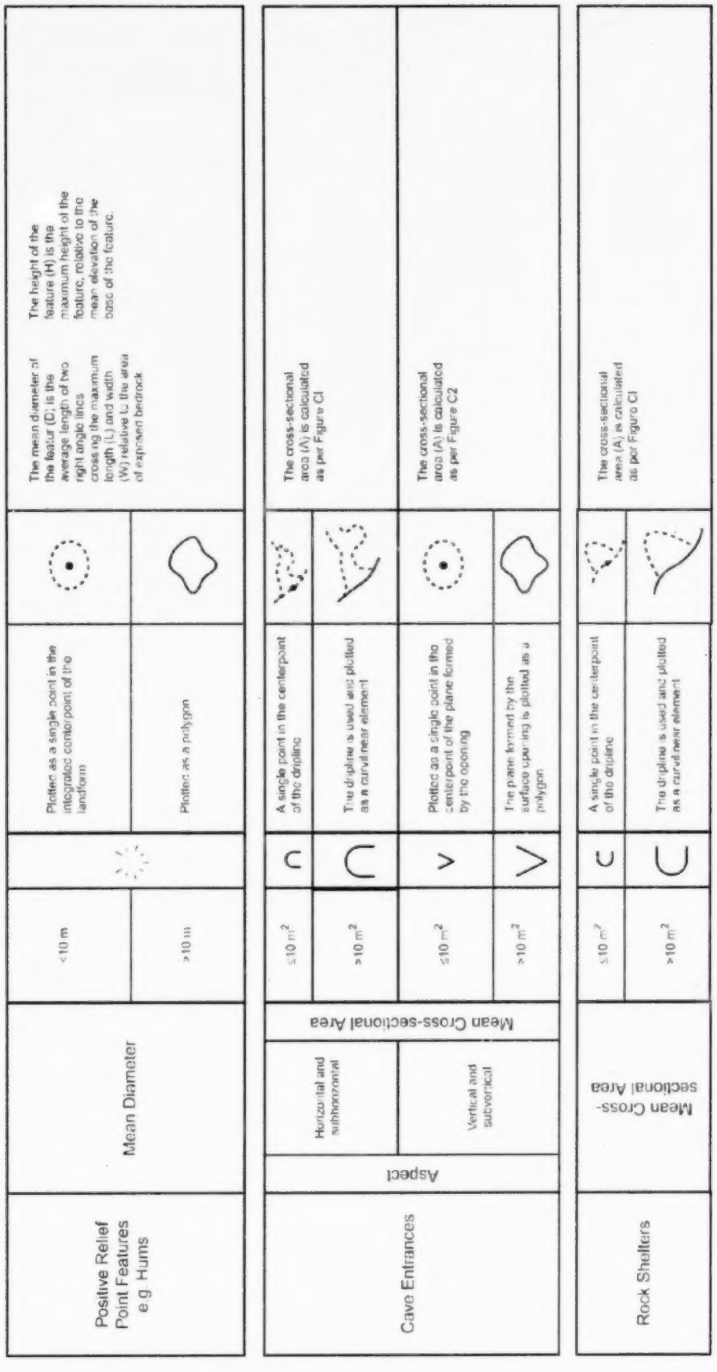

Feature Types
Limits
Symbols
Mapping Elements
Measurement Standards
Positive Relief Point Features e.g. Hums
Mean Diameter
<10 m
>10 m
Plotted as a single point in the integrated center point of the landform
Plotted as a polygon
The mean diameter of the feature (D) is the average length of two right angle lines crossing the maximum length (L) and width (W) relative to the area of exposed bedrock
The height of the feature (H) is the maximum height of the feature, relative to the mean elevation of the base of the feature.
Cave Entrances
Aspect
Horizontal and subhorizontal
Vertical and subvertical
Mean Cross-sectional Area
≤10 m²
>10 m²
≤10 m²
>10 m²
A single point in the centerpoint of the dripline
The dripline is used and plotted as a curvilinear element
Plotted as a single point in the centerpoint of the plane formed by the opening
The plane formed by the surface opening is plotted as a polygon
The cross-sectional area (A) is calculated as per Figure C1
The cross-sectional area (A) is calculated as per Figure C2
Rock Shelters
Mean Cross-sectional Area
≤10 m²
>10 m²
A single point in the centerpoint of the dripline
The dripline is used and plotted as a curvilinear element
The cross-sectional area (A) is calculated as per Figure C1

Figure D1. Continued.

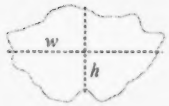
Profile view

Circular entrance of radius r

$$A = \pi r^2$$

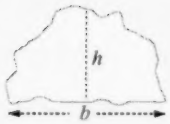
Elliptical entrance of height h and width w

$$A = \pi hw$$



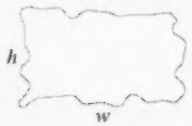
Parabolic entrance of height h and base b

$$A = \frac{2}{3} hb$$



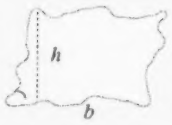
Rectangular entrance of height h and width w

$$A = hw$$



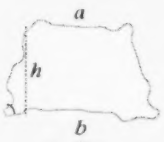
Parallelogram-shaped entrance of height h and base b

$$A = bh$$



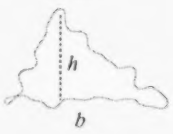
Trapezoidal entrance of height h and parallel sides a and b

$$A = \frac{1}{2} h (a + b)$$



Triangular entrance of height h and base b

$$A = \frac{1}{2} bh$$



Note: For inventory purposes, the cross-sectional area of a horizontal or sub-horizontal cave entrance is visually estimated at the vertical plane formed by the most probable dripline. The dripline is a line on the ground at a cave entrance formed by drips from the rock above.

Figure D2. Cross-sectional area of cave entrances with horizontal or sub-horizontal aspect.

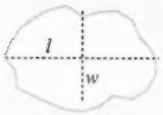
Plan view

Circular entrance of radius r

$$A = \pi r^2$$

Elliptical entrance of length l and width w

$$A = \pi lw$$



Rectangular entrance of length l and width w

$$A = lw$$

Parallelogram-shaped entrance of length l and width w

$$A = lw$$

Note: The cross-sectional area of a vertical or subvertical entrance (e.g., a shaft or grike) is visually measured at the horizontal plane formed by the highest closed contour.

Figure D3. Cross-sectional area of cave entrances with vertical or sub-vertical aspect.

Right circular funnel of radius r and depth h

Volume = 1/3A*h*

where $A = \pi r^2$

Frustrum of right circular funnel of radii *a*, *b* and depth *h*

Volume = $1/3\pi h(a^2 + ab + b^2)$

Spherical bowl of radius *r* and depth *h*

Volume = $1/3\pi h^2(3r\text{-}h)$

Right circular cylinder of radius *r* and depth *h*

Volume = $2\pi rh$

Circular cylinder of radius *r* and slant height *L*

Volume = $\pi r^2 h = \pi r^2 L \sin\theta$

Figure D4. Geometry and volume of depression features.

Appendix E. Searching for cave entrances in old-growth forests: an overview of ground-based methods employed in north and central Vancouver Island, British Columbia

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ABSTRACT

Ground-based methods have been used since 1982 by forest licensees and inventory contractors to search for cave entrances in the remnant old-growth forests of North and Central Vancouver Island. Methods have ranged from a low intensity preliminary reconnaissance to a high intensity saturation search. Moderately intensive sampling methods, such as the grid pattern (i.e., strip) search and judgmental search, will be evaluated for effectiveness and cost efficiency.

INTRODUCTION

The remnant primary old-growth forests of Canada's West Coast are globally rare temperate rainforests.

The forests atop North and Central Vancouver Island's karst are complex ecosystems. Very old and large coniferous trees form a dense canopy, which, combined with frequent fog and precipitation, make aerial detection of all but the largest cave entrances difficult. Consequently, resource managers most commonly employ ground-based search methods to inventory cave entrances in old-growth forest stands.

Methods that have been successfully used by the BC Ministry of Forests and coastal timber licensees include:

a) Reconnaissance (or walkabout)

b) Strip (or transect)

c) Judgmental (or feature-oriented)

d) Total (or saturation)

The search strategies have occasionally been combined and stratified, or at least modified to better suit field conditions. The most appropriate field method depends on the specific objectives of the cave entrance inventory and the nature of the forest environment.

The reconnaissance is normally the least intensive ground search method, while the strip and judgmental, based on systematic sub-sampling, are moderately intensive. Searching can also be very intensive, such as with total surveys (i.e., as would occur in a tight grid network).

All surface inventories usually begin with a desktop review of aerial photography, geological mapping and records of known feature occurrences. These front-end tasks, or "filters", constitute important elements of the stratified inventory.[1]

Background to specific requirement

The specific requirement to locate cave entrances was introduced in the *Cave/Karst Management Handbook for the Vancouver Forest Region*[2] (June 1994) hereinafter referred to as the "Handbook"). Retained in the July 1994 version, the current guideline[3] reads as follows:

"When a proposed development boundary lies within a karst formation, as identified by the L^5 feature in the recreation inventory, a systematic surface inventory to locate cave entrances must be undertaken within this area as well as for the karst formation surrounding the development boundary."

Accordingly, the primary objective of all ground searches is to locate cave entrances to meet this administrative requirement. The information collected as a result is used for updating recreation inventories, the completion of which is required under section 28(d)(i) of the Forest Act.

Surface surveys can also lead into a complete multidisciplinary cave/karst inventory and assessment project, which necessitates the subsurface inspection of found caves. Locating "hydrological" features, such as active insurgences and exsurgences, is also an important precursor to the design of dye tracing studies. Found swallets can be used for the introduction of dye, while springs serve to monitor dye travel.[4] The surface inventory information is also used to enable concurrent or subsequent subsurface inspection of caves. In practice, a secondary objective may be to establish other important biophysical site characteristics (e.g., soils, wildlife, etc.) (This phase of inventorying is beyond the scope of this paper.)

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[1] Photogrammetry can identify certain biophysical indicators (e.g., large tree canopy gaps and surface lineaments that are sometimes associated with cave entrances). Aerial photography can also reveal karst features in adjoining and analogous cutover areas, from which inferences can sometimes be drawn about the closed canopy inventory area.

[2] The Handbook guidelines are optional or voluntary practices not currently in the Forest Practices Code (FPC), but the implication is that they are to be used to meet resource management objectives. The handbook was to have been replaced by the FPC Cave Management Guidebook in preparation. Nonetheless, handbook guidelines can be made legally enforceable when they are inserted in plans, prescriptions and contracts. The MOF Regional Manager requires the interim implementation of the Handbook procedures, including systematic surface inventories, under the authority of a written directive to MOF Districts and licensees.

[3] Previously, MOF management guideline and policy statements prescribed only general cave inventories. The current Handbook also states that the "extent and intensity" of the surface inventories must be approved by the MOF District Resource Officer Recreation.

[4] Dye studies are being used with increased frequency by BC resource managers and recreational cavers to enrich the understanding of the hydrogeology of the more sensitive karst units.

METHODS

Sampling surveys:

The objective of the systematic surface inventory is to gather information about the occurrence of cave entrances over the ground sampled, and to occasionally make inferences about adjacent unsampled terrain. Of the three sampling survey methods described below, only the reconnaissance search is not, strictly speaking, a systematic search (i.e., a search type that is not characterized by a system or method).

Reconnaissance

The reconnaissance is most often used in combination with the judgmental search. The search route usually consists of a transverse line (i.e., a line that crosses from side to side between the boundaries of the inventory area). In addition, it can be used to search along projected road right-of-ways.[5]

This reconnaissance is a type of sampling survey often used as the first field phase of a stratified inventory.

Strip

With the strip search method[6], the general grid layout and orientation of search lines are selected based on practical considerations. Thereafter, the individual search lines are mechanically and uniformly spaced at fixed intervals.

Typically, a single person establishes a search center line with a handheld compass, clinometer and hip chain, while making the necessary observations within the field of view. Two lateral searchers rove over the ground in a "zigzag" fashion on opposite sides of the center line. At a minimum, the azimuth and chained distances are recorded for the center line. Clinometer readings may be taken when traversing sloped terrain.[7]

Depending on the type of karst terrain to be searched, the center line interval (and the width of the strips) is sometimes varied. Inventories have been conducted at 100-m, 50-m and 30-m center line intervals. The visibility and ease of cave entrance recognition under different forest stand conditions may set the optimal balance between these limits. The 90-m width is the most commonly used center

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[5] It is generally accepted that the roadbuilding phase of forest development can produce the greatest impacts.

[6] The strip search was first used in 1982 to inventory selected timber harvest units in the Tahsish River drainage of northwestern Vancouver Island.

[7] More accurate center line surveying can be specified however. To maintain 1:100 horizontal accuracy, for example, the instruments must be capable of readings in one-degree increments. Distance measurements to the nearest 0.1 metre are periodically required by the sponsoring agency or client. Shots average 10-12 m depending on conditions. The survey stations are established in the field and marked. If the search center lines are accurately surveyed, they can be used to tie in features found.

line interval and assumes a mean visible range of 10-15 m. At this interval, the three members of the crew start the search spaced 30-m apart.

The strip method is a technique that is particularly useful when making comparisons between karst zones.

Judgmental

The judgmental search is the second type of systematic sampling survey. The method is based on the recognition that surface karst features do not occur in random order.[8]

By analyzing inventory data, it has been possible to identify the association between surface karst features and one or more terrain variables. These correlations have been verified by regression analysis and established for Vancouver Island forest karst ecosystems. For example, there is shown to be a strong positive or direct correlation between the topographic position of swallets and upper limestone contacts. Conversely, a negative (i.e., inverse) correlation exists between steep hillslopes and dolines. There are many such correlations, learned principally through experience.

Total

Total searches are usually conducted on a regular grid system, with quadrats as small as 20 m by 20 m.[9] They are occasionally employed for small development units, and generally yield the most accurate results.

As with all search methods, the nature and location of notable karst surface features, other than cave entrances, must also be described in field notes, to both characterize the karst terrain and to aid in locating the feature again later.

DISCUSSION

This following discussion is a comparative evaluation of the two most commonly employed methods of systematic surface inventorying – strip and judgmental sampling surveys.

Compliance with applicable guidelines

Both search methods generally satisfy the legislative requirement to perform an orderly and methodical surface inventory, as established in the *Handbook*.

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[8] It was first used to survey selected timber cutblocks in the Holberg area of Northern Vancouver Island, where inventory areas were interspersed with poorly drained transitional fen-bogs and hydrophilic vegetation. The initially mandated ground search of these areas entailed time-consuming and exhaustive fieldwork. (The poorly drained areas did not show many features!)

[9] Strip searching with narrow transects can also lead to complete ground coverage under certain conditions.

Human Resources:

Number of persons required

The minimum crew size for the transect search is three persons, assuming that the center line surveyor uses a hip chain as a distance measurement device. A chained traverse requires a second person on the center line.

The judgmental search method generally requires fewer persons over shorter periods. In theory, one person can perform this type of surface survey, provided that provincial safety and client policy requirements are met.[10]

Required skills

The relatively higher cost of the strip search (See "Estimated Costs"), and higher crew complement, can lead to the use of less skilled and inexperienced labour. Although most persons can readily recognize classic cave entrances, difficulties in interpreting the full range of certain karst characteristics associated with unusual or uncommon atmospheric openings can bias the search. These are not inconsequential problems if systematically repeated throughout the inventory unit.

The judgmental search generally requires a higher skill level than that called for in grid or transects searching and this can add to the cost. This eventuates in higher quality documentary output, however.

Lower turnover can help to ensure consistency between searchers.

Duplication of effort:

This strip method does not efficiently take into account for the field knowledge acquired by forest workers who may have already traversed the inventory area, many of whom can reliably recognize cave entrances. The reliability of karst-specific observations made by these workers has steadily improved over recent years. Indeed their capability can exceed that of sport cavers, who, perhaps because of their location and/or interests, may have been minimally involved in searching for caves in old-growth forest.

Timing and scheduling

The longer duration of the strip search, unless multiple crews are deployed, means that it is potentially subject to more frequent weather-related interruptions and delays (e.g., hazardous windstorms, snowfalls, etc.). This becomes an important limiting factor in remote locations where access is by air transport or watercraft.

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[10] It is permissible for one person to work alone) if a means of periodically checking the well being of this individual is instituted pursuant to Section 8.32 ("Men Working Alone") of the BC Industrial Health and Safety Regulation. This procedure entails a scheduled check-in by portable VHF radio. In practice, however, a minimum two-person crew is deployed in during periods of inclement weather and/or in remote forest development areas. Transceivers are also used in cases where voice communication between workers is not possible.

Efficiency

One of the drawbacks of the strip search arises arises from the fact that karst surface features (e.g., cave entrances) are not evenly spaced over the entire inventory unit, but are determined by topography and clustered. This can sometimes mean that broad tracts of land are sampled where no significant features are found. Such is particularly the case when the nature and/or depth of the regolith may have masked, or almost completely obscured, the surface expressions of the karst formation.

Cave entrances are frequently controlled or at least influenced by topography. For example, in hillslope areas, swallet-type cave entrances are most likely found where surface streams intersect the upper limestone contact. As ellipsoid features, with a tendency toward downslope orientation, these swallets are not as quickly located if the multiple strips are run across the hillslope, and below the contact zone.

With the judgmental search, the field personnel can usually be deployed more efficiently. For example, each person can follow separate pre-designated search routes. As well, persons can handle separate field tasks in the same zone concurrently.

Rate of progression

A limiting factor for the strip search can be the sponsoring agency's or client's requirement to accurately survey the center line.[11] As the center line surveyor is generally the slowest person in the three-person crew, lateral searchers must accommodate this to maintain their position relative to the center line. One of the advantages of the strip search is that the surveyed center lines are available for accurate entrance tie-ins.

In addition, the field tasks are generally more onerous for one lateral searcher than for the other. This is particularly true when multiple karst surface features are found. Hence one lateral searcher must periodically wait for the other. Although pacing distances is much quicker and easier, especially for independent searchers or in shrubby or dense forests, it is less accurate than chaining. Transect distances and cave entrances along transects are measured by using metric hip chains.

Obstacle areas:

Problems can arise when a strip is constrained to a straight-line course over obstacles (e.g., short steep bluffs, perched bogs, windfall areas, etc.). The rate of progression is negatively impacted when such difficult zones are traversed and the lateral searchers are deflected off of their search route axes. Furthermore, these areas frequently exhibit lower karst cave entrance potential except at the periphery.

[11] Resource managers have occasionally required surveying search routes to 1:100 accuracy. This involves the use of a hand-held compass and clinometer.

Of the two sampling survey methods, the judgmental search better lends itself to where there are extensive patches of dense undergrowth or windthrow on uniform terrain. These occurrences are rarely associated with cave entrances. While the strip search center line must generally follow a compass course through these patches, the judgmental searcher is not bound to a straight-line compass traverse. The latter searcher can circumvent these osbtacles whenever necessary.

Sampling bias

The probability of finding a cave entrance using the strip method largely depends on its size (assuming symmetry in all other respects). Entrances must be large enough to see at a reasonable viewing distance. (Note: A dry (i.e., noiseless) pit measuring 0.25 metre across can easily be missed at a distance of 10 m with moderate understory.) Thus, large entrances are more likely to be found than small ones.

Similarly, sampling biases can occur when an inexperienced observer underestimates the potential of karst land units with few surface karst expressions. How thoroughly the ground is searched will also depend on the care exhibited by individuals -- the less perceptive searchers will tend to miss features.

Failure to locate a cave entrance could result from this bias. In addition, individual bias can be introduced by the differing physical stamina of lateral searchers. For example, more enthusiastic and energetic lateral searchers will tend to cover more ground (i.e., the overall amplitude of the "zigzags" tend to be greater). If lateral searchers are imperfectly matched, then the overall rate of progression is reduced to that of the slowest person.

The judgmental method is not as biased toward large cave entrances, as all features along the access route and the target zone are more likely to be inspected. Size distributions of entrances obtained by this method cannot be compared directly to results provided by the other methods.

Cave entrances of all types may be more easily missed when wide center line intervals and strips are used. Ten-metre wide strips can increase the number of small entrances found. However, if larger entrances are the primary object of the surface survey (e.g., because they are more likely to be penetrable), then narrower grids may not be advantageous.

A particular potential bias toward finding large cave entrances exists because the center line searcher more readily sees them. Entrances at the limit of his visibility range, but still within the middle strip, will be missed more often than in the lateral strips. this is due to the fact that the center line person does not normally break the chain to inspect collateral features or to "zigzag".

Another potential bias arises between the lateral searchers themselves. The probability of finding an entrance in a homogeneous land unit is roughly proportional to the amplitude and length of the search path wave or "zigzag" (i.e., the distance traveled). Assuming the same visibility range, the probability is

greater if the searcher increases the amplitude of the "zigzag". Wider strips should result in finding more entrances than narrow or line transects, and the effect would be greatest for small entrances.

Coverage

If a 90-m interval search line is selected and a 15-m lateral visibility range is assumed for equidistant searchers, then a 100% sample is theoretically possible with the strip method. In practice, however, the actual sample size is highly variable when the terrain is broken and where poor visibility conditions prevail. Inventory contractors have reported that a 50-80 percent sample is possible under optimal conditions.

Right-of-ways

Unless the projected right-of-ways can be used as reference or base lines, the non-rectilinear layout means they can be searched only by the intersecting fixed search lines, and the random intersections of lateral search routes. These intersections can occur at perpendicular and oblique angles on hill slopes.

This judgmental method can be efficiently employed to search along projected road right-of-ways. The method allows for efficient linear searching of projected right-of-ways, particularly those that traverse across hill slopes. One person can usually search the standard road width from the center line assuming a visibility range of 15 m.

Concurrent tasks

For strip searches, concurrent subsurface inspection of complex and/or technically difficult caves necessitates lengthier surface carries. The requisite heavy loads of harnesses, rope, and hardware are transported over search paths or cached at intervals. This reduces the overall rate of progression. Judgmental searchers tend to carry the gear for preliminary subsurface inspections of caves at all times.

Other karst surface features and terrain characteristics

Strip searching for more common karst surface features (e.g., dolines) allows the searcher to make more precise determinations about karstification (e.g., index of subsurface karstification[12]). However, in the case of narrow transects there is no guarantee that the unsampled features that lie outside the transect are as numerous as inside the transect.

In the judgmental search, the knowledgeable searcher can design traverse routes to make some inference about the karstification of the unsampled portion of the inventory area. The level of experience required is higher though.

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[12] The karstification index is the number, expressed in square kilometres of apertures of karstic conduits (e.g., swallets, dolines, exsurgences, etc.) which can be detected on the surface of the karst. The index of subsurface karstification is the sum of discrete karst surface features sampled divided by the total area of the strip transects.

Estimated cost

The average cost of strip searching varies according to center line interval -- for lines established at 90-m intervals, and to 1:100 survey accuracy, it ranges $200-250 per hectare. This cost estimate includes the associated field tasks (e.g., entrance identification).

The cost range for judgmental searching is $50-80 per hectare. In judgmental sampling, a search area is divided into zones of known higher probability, and traverses are selected by an experienced contractor for the purpose of sampling these zones. This approach has several advantages. If search routes are carefully selected, the results will be obtained in less time than required for a systematic grid or transect search. Aside from the temporal efficiency, the overall cost of the search will be much more favorable.

CONCLUSIONS

For most inventories in large forest tracts, it has not been economically feasible to search 100 percent of an inventory area. The number of field workers required and the manner in which they can be deployed greatly influence the cost of a survey. Aside from cost, the time required to complete more intensive searches is also a major consideration.

Larger units may require many repeat visits and take several years to complete. Administrative timelines and ground access problems (e.g., inclement weather) are often important constraining factors.

The prevailing compromise is to use a moderately intensive method and to randomly exclude many of the smaller features from more detailed fieldwork. Field time is thereby most profitably employed on the cave entrances of primary interest and importance.

Carefully designed sampling surveys have become an accepted method of inventorying for cave entrances in forest development units that cannot be completely searched due to time and cost constraints.

Though the statistics for finding entrances and of projecting the number of unsampled entrances have not been developed for the two systematic sampling methods, strip and judgmental, it is believed that for a given land unit they produce similar results.

The strip search appears to be most useful where cave/karst features (i.e., possible cave entrances) are spread more diffusely or homogeneously through the understory, instead of being concentrated in discrete locations. The judgmental search is better for finding small features and is less costly if the experienced searcher can predict where features are more likely to be found or not found -- search routes are designed and optimized accordingly.

The risk of not finding the features that may occur in unselected routes or adjacent zones is minimized by carefully designing search routes, adjusting the

search intensity (i.e., stratified sampling), and by utilizing knowledgeable and experienced field workers.

Note:

In the course of preparing this review we have discovered a possible application to future searches for persons reported missing from caves unknown to the BC Cave Rescue organization.

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NOTE: The glossary, addendum and appendix from this paper are not included here.

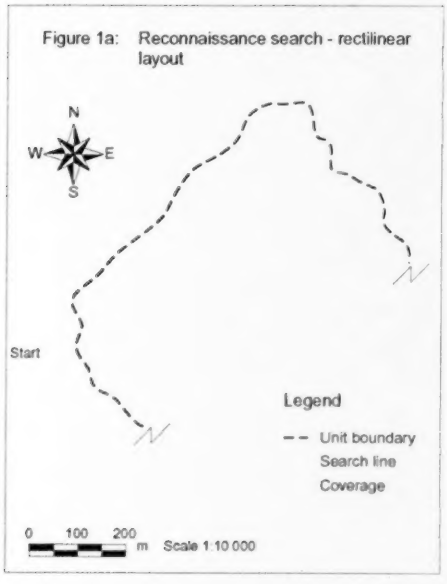


Figure 1a: Reconnaissance search - rectilinear layout

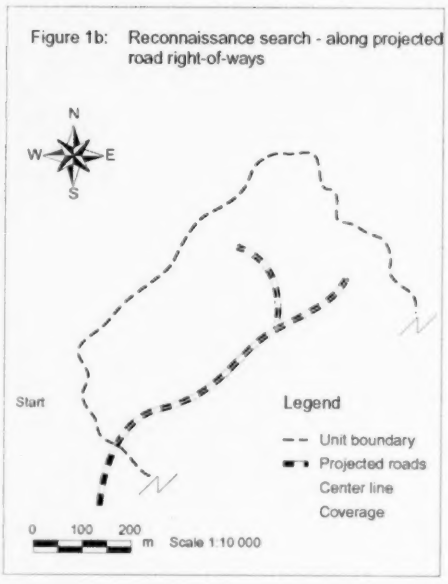


Figure 1b: Reconnaissance search - along projected road right-of-ways

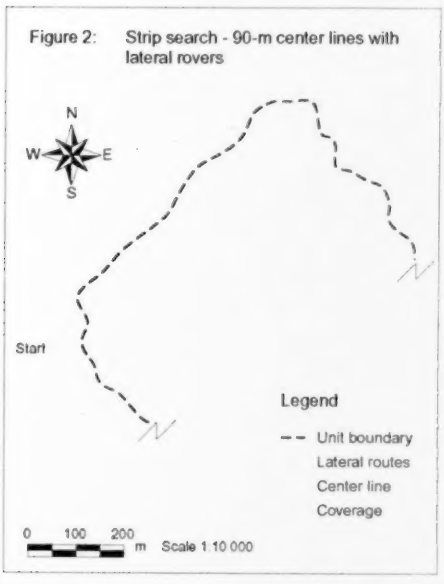


Figure 2: Strip search - 90-m center lines with lateral rovers

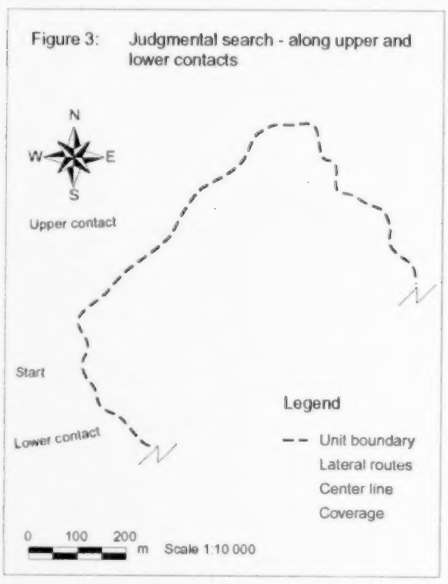


Figure 3: Judgmental search - along upper and lower contacts

Figure 4: Total search

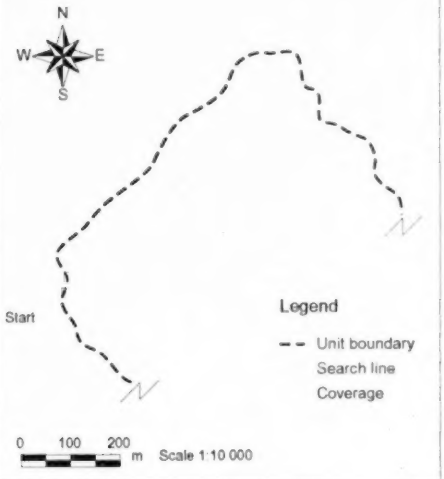


Figure 5: Swallet detection with judgmental search

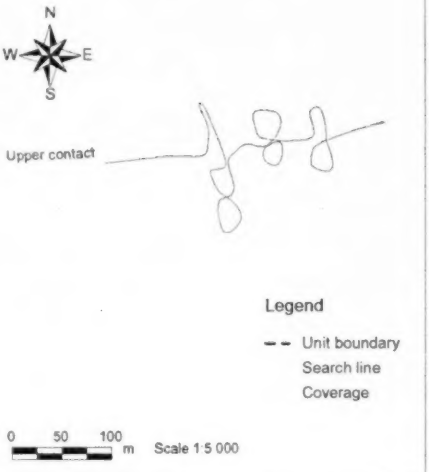


Figure 6a: Encountering fens with judgmental search

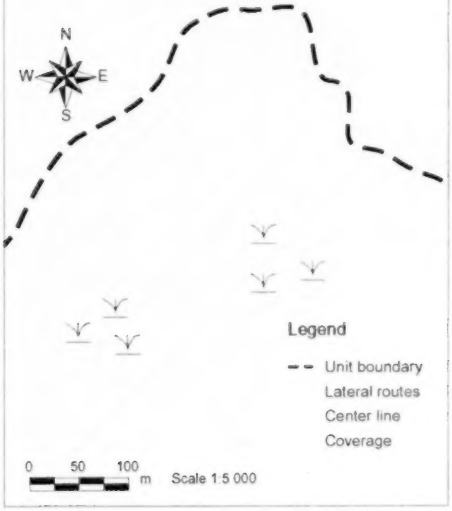


Figure 6b: Circumventing fens with judgmental search

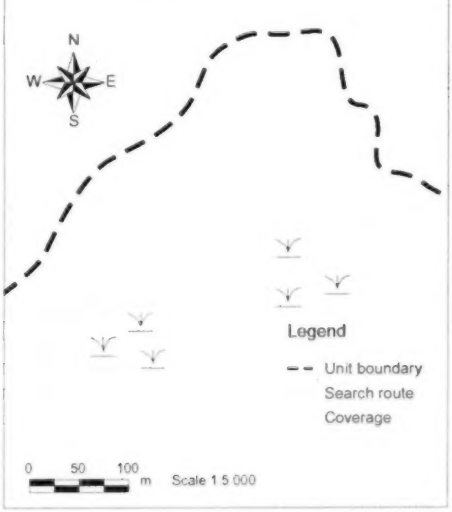
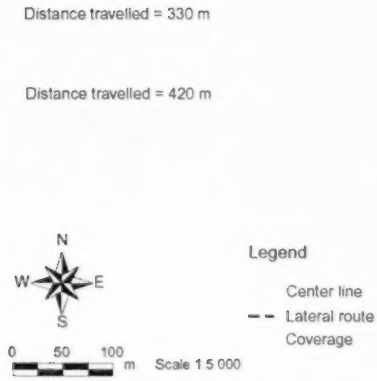


Figure 7: Amplitude versus frequency of lateral search routes

Figure 8: Distance travelled - center line versus lateral route



Appendix F. Subsurface mapping symbol list (International Speleological Union) and cave inventory coding key and classification card (Vancouver Forest Region of British Columbia)

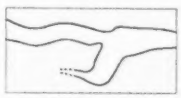
New UIS Cave Symbols

Main measuring points

Passage outline

Underlying passage

Continuation, too tight



Continuation, possible

Presumed size

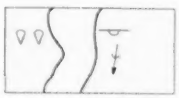
Ceiling form

Dripline
(start of cave)
Profile
(arrow in line of view)

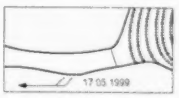
Drop
(height in meters)

Pit (depth in meters)

Scallops – flutes in general
Direction of paleoflow



Air draft
(with date in dd/mm/yy format) –
Ice-snow-firn

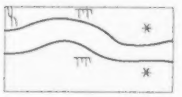


Stalagmites

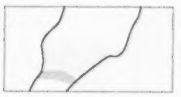
Stalactites

Sinter Curtains
Pillars

Helictites
Soda straws
Crystals



Sinter pools



Flowstone –
Wall calcite –
Moonmilk –

North arrow –
Geographic
Cartesian and Magnetic

Blocks –
debris

New UIS Cave Symbols (Cont'd)

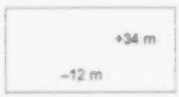
Pit, open to surface

Aven – Aven-pit

Contour lines
(altitude in meters) –
Gradient arrows
Entrance arrow

Gradient lines
(altitude above sea level)

Difference in elevation
(height in meters)
Joint – fault – inclined joint



Lake
Flowing water

Sump

Cascade
Waterfall

Spring –
Sink

Diffuse water inlet –
Seep

Pebbles

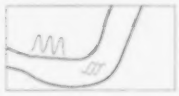
Clastic sediments
Sand-silt-clay-humus

Clay-covered walls

Guano

Camp

Anastomosen –
Karren



Cave popcorn –
Disk

Bones

Human activity
(pictograph, burial site,
mining site...)

Height of room
(height in meters)

Coding Key for Cave and Karst Inventory and Classification

1. **Cave number** – Permanent reference number to be assigned by a central Provincial clearing house once a satisfactory numbering system has been worked out.
2. **Cave name** – Assign name. Make sure name is unused. Some caves are already known by several names. In this case, the following is suggested for final name assigning:
   A. Historic name or name given by first person discovering cave.
   B. If "A" is indeterminable, use the name which is most descriptive of the cave.
   C. List all other names on separate cards, with a reference to the final assigned cave name.
      1. List all other names under "remarks."
      2. List all other names in master cave file.
3. **Map** – Record the National Topographic Series 1:50 000 scale map reference number and name (e.g. 92 C/16 Cowichan Lake).
4. **Latitude** – Degrees, minutes and seconds as near as can be calculated.
5. **Longitude** – Degrees, minutes and seconds as near as can be calculated.
6. **Plotted** – Indicate if cave has been plotted onto a map or overlay. Y – yes, N – no. Record scale if plotted (e.g. Y-50 000).
7. **Air photo number** – Record the number of the air photo on which the cave is pinpointed.
8. **Elevation of entrance** – Either of the following:
   A. Altimeter reading recorded in metres, e.g. A1023
   B. Estimated elevation from contour map, recorded in metres, e.g. E 1020.
9. **Status of land** – Legal status of land on which cave or cave entrance is located:

PRI – private land	PP – Provincial Park
FOR – Provincial Forest Reserve	NP – National Park
VCL – vacant Crown land	ER – Ecological Reserve
LAR – Land Act Reserve	M – other; explain in "remarks"

10. **Geological formation** – List all formations which intersect cave passages.
11. **Legal location** – Legal description of lot or licence (e.g., Hourglass Cave would be "T.L. 5759, Juan de Fuca Provincial Forest"; Cascade Cave would be "B.K. 89, Folio No. 01-2189, Tree Farm 13 of T.F.L. 20"). Owner or licensee could be noted in "remarks."
12. **Records** – Organization or agency initiating file or holding most file material on cave (na).
13. **Type of cave**

C – coast or littoral	L – lava tube	S – solution
F – fissure	P – pit only	T – talus
G – glacier	R – rock shelter	

14. **Dominant rock type**

CO – conglomerate	TR – travertine	SO – soil
DO – dolomite	LS – limestone	SS – sandstone
GY – gypsum	MX – other metamorphic	MA – marble
IG – igneous	SH – shale	O – other

15. **Type of entrance –** Code as many as apply, starting with the "main" entrance.
    L – large horizontal (more than 3 m × 3 m or 10 sq. metres)
    H – small horizontal (less than 3 m × 3 m or less than 10 sq. metres)
    V – large vertical (same as "L" above)
    S – small vertical (same as "H" above)
    B – side or bottom of sinkhole
    Q – quarry or road cut gives access
16. **Number of entrances**
    1, 2, 3 etc.
17. **Length of all known passages**
    A. Surveyed length in metres – S1243
    B. Estimated length in metres, approximate – A 1240
18. **Pattern of cave**

P – single passage/room only	D – dendritic pattern, bifurcating
P – pit only, no passages or rooms	M – maze, boneyard, solution, network
R – rectilinear pattern	T – trellis/joint control maze

19. **Trend of cave from entrance** – Express in a bearing on the 360° scale
20. **Vertical relief of cave** – Highest ceiling to lowest floor.
    A. Surveyed relief in metres – S154
    B. Approximate relief in metres – A150.
21. **Water element** – Code as may apply.

A – arid, no water	M – moist earth
D – dripping water	P – pool present (less than listed for lakes)
F – flooded	S – stream or river system in cave
I – intermittently flooded	

    L – lakes present (9 sq. metres of surface area, plus an average of at least 15 cm deep).
22. **Hazards present** – Code as many as apply. Supply details under "remarks" if required.

B – biological hazards (animals, poisonous insects or reptiles, etc.)	L – loose rocks or collapse hazard
	R – underground rescue problems
C – length and/or complexity	T – tight or awkward passages
E – surface evacuation problems	V – long, exposed drops or pitches requiring tackle
F – intermittent or regular flooding	W – water with no alternate route
G – toxic gasses present	P – polluted water
H – hypothermia hazard (low temperature, exposure to water, etc.)	N – none

23. **Technical Grade**

Grade 1 – Easy cave; no pitches or difficulties

Grade 2 – Caves without any particular hazardous, difficult or strenuous sections; but may contain small drops and offer some degree of challenge to the caver

Grade 3 – Caves that present some hazard or difficulty to the caver; (i.e., squeeze, large underground pitch, difficult traverse, etc.)

Grade 4 – Caves which include very strenuous sections or large and wet underground pitches

24. **Cave contents** – Codes as many as apply.

A – archaeological (artifacts, pictographs, etc.)

B – biological (organisms)

G – geological structural, hydrological, genetic)

H – historical

P – paleontological (fossils) (H)

S – speleothems

N – none. Cave, shelter or sink of no special attraction or significance.

T – taphonomic deposits

25. **Appeal Factor**

Low (L) – Caves with no appeal to cavers and/or the general public

Medium (M) – Caves of moderate appeal to cavers and/or the general public.

26. **Feature significance as identified in the recreation inventory**

A – very high capability to attract recreational, educational or scientific use (provincial or higher scope)

B – high capability to attract recreational, educational or scientific use (regional scope)

C – moderate ability to attract recreational, educational or scientific use (local scope)

D – limited ability to attract recreational, educational or scientific use

27. **Management class as identified in the recreation inventory**

0 – Area of outstanding recreational, educational, scientific or heritage value and is most appropriately managed for these values

1 – Area requires special management considerations to protect or maintain recreation, education, scientific or heritage values

2 – Normal forest management practices are adequate to maintain recreation values of the area

28. **Cave marked at entrance with a benchmark or survey reference point**

Y – yes; N – no

29. **Cave classification code**

Surface management type/Subsurface management type: (A,B,C/1,2,3)

Refer to detailed explanation of classification type, Sections B and C of the handbook.

Ministry of Forests Cave Inventory and Classification Card

Province of British Columbia

Ministry of Forests

1. CAVE No.

CAVE/KARST INVENTORY AND CLASSIFICATION RECORD

1. CAVE NAME						2. MAP					
4. 0 1 2			5. 0 1 2			6. PLOT					
7. AIR			8. ELEVATION			9. STATUS					
10. GEOLOGICAL FORMATION											
11. LEGAL LOCATION											
12	13	14	15	16	17	18	19	20	21	22	23
24		25	26	27	28	29			DATE PREPARED Y M D		

FS 311 REC 81/8

see reverse

REMARKS: _____

Appendix G. KFA field cards

KFA FIELD CARD #1 – CAVE SURVEY DATA FORM

DATE: Y	M	D	RECORDED BY:
LOCATION:			

LEG	LENGTH	AZIMUTH	SLOPE	LEFT ←	RIGHT →	UP ↑	DOWN ↓

KFA FIELD CARD #2 - SURFACE KARST FEATURE RECORD

FEATURE ID	FEATURE TYPE	LOCATION	DIMENSIONS (width/length/depth)	DESCRIPTION	PHOTO

KFA FIELD CARD #3 – SURFACE KARST FEATURE SIGNIFICANCE EVALUATION

DATE: Y	**M**	**D**	**RECORDED BY:**
KARST FEATURE NO.			**LOCATION:**
KARST FEATURE DESCRIPTION:			

Characteristic/Value	L	M	H		Comments
Dimensional Characteristics					
Connectivity					
Hydrology					
Geological					
Biological					
Scientific/Educational					
Archaeological/ Cultural					
Recreational/ Commercial					
Rarity/Abundance					
Visual Quality					
Other:					

OVERALL SIGNIFICANCE: ❑ Significant ❑ Non Significant

PRESCRIPTION COMMENTS: _____

_____

_____

KFA FIELD CARD #4 – KARST VULNERABILITY DATA

DATE:	RECORDED BY:
LOCATION:	POLYGON NUMBER:

EPIKARST DEVELOPMENT RATING: ❑ slight ❑ moderate ❑ high ❑ very high
Confirmed by calibration plot ❑ yes ❑ no
Average soil thickness ❑ bedrock ❑ 2–20 cm ❑ 20–50 cm ❑ 50–100 cm
❑ 100–200 cm ❑ >200 cm
Erodible, fine-textured soils present: ❑ yes ❑ no (if yes, raise rating below by one level)

EPIKARST SENSITIVITY RATING:

Epikarst Development Rating		Average Soil Depth (cm)					
		>200	100–200	50–100	20–50	<20	Bedrock
	Slight	Low	Low	Low	Low	Low	Low
	Mod.	Low	Low	Low	Mod.	Mod.	Moderate
	High	Low	Low	Mod.	Mod.	High	High
	Very High	Low	Low	Mod.	High	Very High	Very High

SURFACE KARST FEATURE DENSITY
❑ very low ❑ low 1–5 ❑ moderate 5–10 ❑ high 10–20 ❑ very high >20
Roughness modifier required ❑ yes ❑ no (if yes, raise rating below by one level)

SURFACE KARST SENSITIVITY RATING

Epikarst Sensitivity Rating		Surface Karst Feature Density				
		0	1–5	5–10	10–20	>20
	Low	Low	Low	Mod.	High	High
	Mod.	Low	Mod.	Mod.	High	High
	High	Mod.	Mod.	High	High	Very High
	Very High	Mod.	High	High	Very High	Very High

KFA FIELD CARD #4 (CONT'D) – KARST VULNERABILITY DATA

SUBSURFACE KARST POTENTIAL RATING

	Geology	Topography	Hydrology	Knowledge of karst
Low Subsurface Potential	Impure carbonates	Lower relative elevation as compared to surrounding terrain	No evidence of water sinking or emerging	No known subsurface karst in bedrock unit
Moderate Subsurface Potential	Moderately pure carbonates	Steep slopes with small breaks	Minor springs/ leaking creeks	Known caves in bedrock unit at similar sites
High Subsurface Potential	Pure (white) carbonates	Benches or breaks in slopes below likely recharge areas	Swallets and springs No surface drainage	Known caves within area of interest

❑ low ❑ moderate ❑ high

MODIFIER FOR KARST FLORA/FAUNA OR HABITAT SITES REQUIRED

❑ Yes ❑ No (if yes, raise rating below by one or two levels)

KARST SYSTEM VULNERABILITY:

OVERALL SURFACE KARST SENSITIVITY	SUBSURFACE KARST POTENTIAL		
	Low	Moderate	High
Low	Low	Low	Moderate
Moderate	Low	Moderate	High
High	Moderate	High	Very High
Very High	High	Very High	Very High

❑ Low ❑ Moderate ❑ High ❑ Very High

GEOMORPHIC HAZARDS: _____

RECOMMENDATIONS: _____

_____

_____